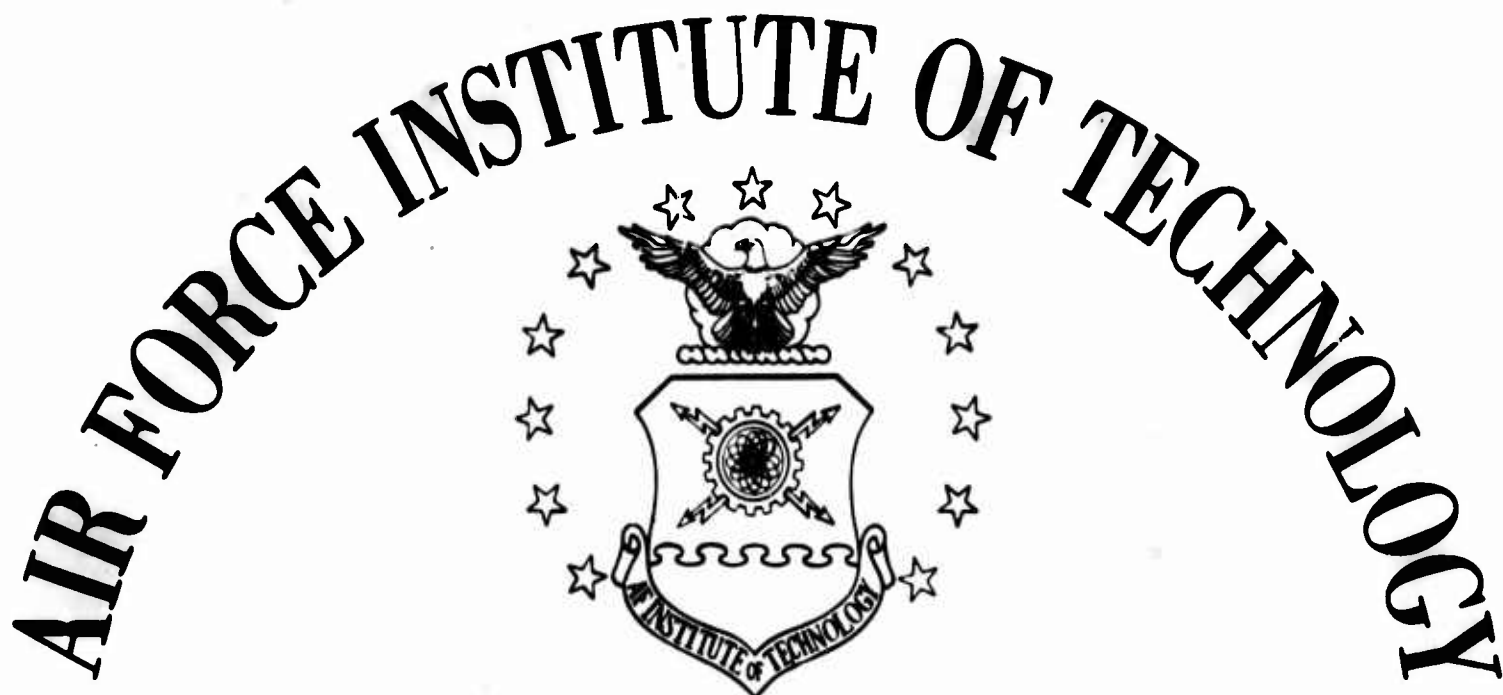
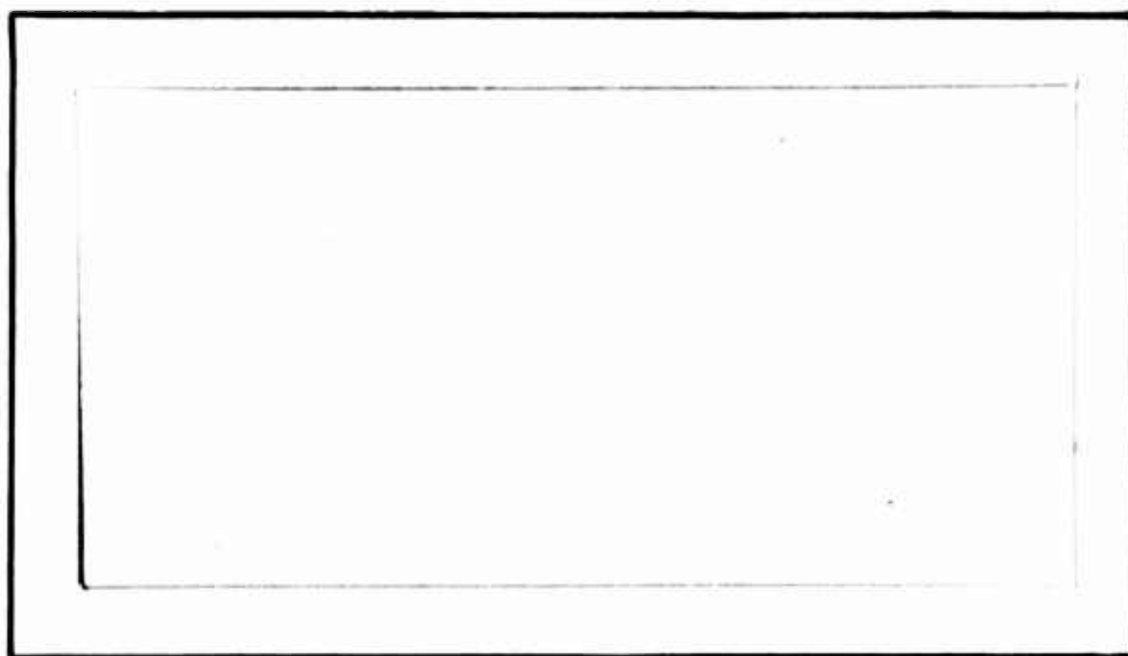


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**FEASIBILITY STUDY OF AN EXPANDABLE
SPACE MAINTENANCE HANGAR**

THESIS

**Presented to the Faculty of the School of Engineering of
the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science**

by

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March 1966

Preface

I undertook this study primarily because I felt that in the near future there will be a maintenance requirement in space. With this maintenance requirement comes the possibility that some type of hangar might be used to afford the astronauts protection from the space environment. Of the different types of space hangar concepts, the expandable type seemed not only the most practical but also the most interesting. Therefore, I undertook this study to determine if it is feasible to design a wall, using primarily organic materials, for a large manned space structure.

I would like to thank my sponsor, Mr. F.W. Forbes, of the Aero-Propulsion Laboratory for his help in this study. I wish to express my appreciation to the GCA Viron Division of Minneapolis, Minnesota and the Whittaker Corporation of San Diego, California, whose prompt and informative answers to my inquiries were greatly appreciated. I would like to thank Major D.E. Evans of the Department of Physics who offered many useful suggestions concerning the radiation portion of this study. Also, a humble thanks is extended to the many persons assigned to the different laboratories here at Wright-Patterson who offered their time, ideas, and suggestions. Finally, I

wish to thank my thesis advisor, Captain S.W. Johnson, of the Department of Mechanics, whose encouragement and sense of direction allowed me to complete this study and my thesis committee, Doctor J.S. Przemieniecki and Lieutenant Colonel C.D. Bailey, both of the Department of Mechanics, whose help and interest made them very approachable in all matters.

Michael R. Keating

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Abstract

To determine the feasibility of an expandable space hangar, a composite wall using polyester terephthalate, 181 style glass cloth, polyurethane foam, and polyvinylidene chloride is designed to operate in a 500 kilometer circular orbit. The structure is cylindrical with hemispherical ends and has a length of 65 feet and a diameter of 25 feet. The wall affords occupants protection from radiation and meteoroids, has a low gas permeability, withstands an internal pressure of 7.5 lb/in^2 , and can be compressed into a launch package of 460 ft^3 . It is concluded that a design of an expandable space hangar is feasible.

FEASIBILITY STUDY OF AN EXPANDABLE SPACE MAINTENANCE HANGAR

I. Introduction

Within the last few years, man has been able to realize the value of weather, communication, and scientific research satellites. Even though present technology has enabled man to produce highly reliable equipment, technology has not enabled him to produce equipment which is 100 percent reliable. Because of the present economic and technical situation, it is more economical to completely replace malfunctioning satellites rather than perform maintenance on them. This situation is primarily due to the fact that space exploration is now in the experimental phase and that no space maintenance capability exists. However, it is conceivable that in the near future, it may be more economical to perform emergency and periodic maintenance on satellites to obtain the maximum use of these satellites.

Space maintenance is defined as the ability to perform maintenance on a space vehicle sometime between launch and recovery. This ability would afford man the capability to assemble, maintain, repair, and replace components of a space vehicle in a space environment. Because of the

hazards and problems imposed in the space environment, the capability of performing maintenance in space is actually very difficult to achieve. The two major problems to be considered in the successful accomplishment of space maintenance are man's ability to perform maintenance tasks in the weightless environment of space and man's physiological limitations due to the hazardous environment of space.

A discussion of man's ability to perform maintenance tasks in a weightless environment is beyond the scope of this study. The most important consideration for extra-vehicular maintenance excursions is the protection of man against the environment. The three categories of protection which can be afforded man are the space suit, the space capsule, and the space hangar.

Briefly, these three protective concepts differ by the length of time they are able to support man outside the spacecraft. May, et al. (Ref 11:147) state that research on space suits over the next five years will give man the capability for at least a two-hour excursion outside his vehicle. The space capsule is a hard shell which encloses the astronaut and can increase his stay outside the spacecraft from 8 to 12 hours. However, the space capsule has two very significant disadvantages. One disadvantage is the weight (700 to 800 lbs) and the other disadvantage is that with it man must use manipulators which will greatly increase the time required to accomplish a task. The

space hangar concept is desirable because it not only affords man protection from the space environment but also permits him to work with his hands and without a cumbersome inflated space suit.

The three space maintenance hangar concepts are the rigid cylinder hangar, the telescoping hangar, and the expandable hangar. Each of these concepts have definite advantages and disadvantages which are now briefly discussed.

The rigid cylinder hangar is simply an aluminum or similar metal cylinder. The rigid cylinder hangar has three main advantages of considerable merit. First, considerable knowledge on the design procedures exists for pressurized double wall metal cylinders. Second, the hangar can use materials with relatively well-known properties. Third, the completely assembled hangar can be operationally checked on the ground before being inserted into space. The primary disadvantage of a rigid cylinder hangar is the size limitation. Since the diameter of the hangar would have to be compatible with the diameter of the launch booster, it is unrealistic, considering the size of even the largest booster, to attempt to put a hangar more than 25 feet in diameter into orbit. It is realized, of course, that the inside of such a hangar could be used to transport secondary cargo into space.

In view of the previous discussion of the rigid cylinder hangar, it appears that the only practicable method for placing a large-scale hangar into space requires the use of some type of telescoping or expandable structure. The telescoping hangar concept has the advantage that the hangar could use well-known inorganic materials and that the overall length of the hangar could be significantly reduced during the launch. However, there are several significant disadvantages associated with the telescoping hangar. Although its overall length can be reduced, its diameter, which is normally the most critical launch package dimension, can not normally be reduced for launch. Furthermore, May, et al. (Ref 11:154) point out that a study made by the Martin Company indicates that a telescoping structure designed for a specific task would weigh about 1.4 times as much as a rigid conventional cylinder designed for the same task. Finally, because there are considerably more joints in a telescoping structure than in a rigid cylinder, the leakage rate of the artificial environment for the telescoping structure would undoubtedly be higher.

The expandable hangar is defined as a shelter, designed primarily for maintenance, that can be expanded from a small volume into a larger volume and that uses primarily organic materials for its walls. This concept can be an inflatable nonrigid structure such as Echo I and

Echo II or can be a chemically rigidized structure. The obvious advantage of this concept is the ability to reduce its package volume during shipment. The primary disadvantage of this concept is that the reliability of the expandable hangar is somewhat less than that of a rigid hangar because of the possibility of the former failing to deploy or rigidize.

No proposed design of an expandable space maintenance hangar was found in the review of the literature. However, a design of an expandable airlock has been proposed by the Whittaker Corporation (Ref 1) and a design of an expandable crew transfer tunnel for space vehicles has been proposed by the Goodyear Corporation (Ref 9). These two proposed designs were of only limited value in this study because they are considerably smaller than a space hangar and because they are not designed to operate for extended periods of time.

II. Definition of the Problem

Purpose

The purpose of this study is to investigate the feasibility of designing an expandable space maintenance hangar. In order for such a design to be considered feasible, this study requires that a wall be designed which affords the astronauts protection from the space environment, that this wall be constructed from materials which would enable it to be packaged into a small volume for launch, and that the structure automatically deploy and cure in space. It is assumed that if the wall can be built the other problems associated with the design can be solved. The construction of doors, hatches, and an internal structure to carry maintenance loads is not considered.

The primary purpose of the hangar is to facilitate maintenance in space by affording the astronauts protection from the hazards of space. A secondary use of the hangar is as an emergency rescue vehicle, but this concept is beyond the scope of this study. This study considers only the expandable hangar concept, and no attempt is made to compare the expandable hangar concept with either the rigid cylinder hangar concept or the telescoping hangar concept.

Design Criteria

This feasibility study is based on the criteria that the hangar operates in a low earth orbit, has an operating internal pressure of 7.5 lb/in^2 , affords the occupants satisfactory protection from the space environment, and has a life expectancy of one year.

A low earth orbit is defined as an orbit between 200 and 500 kilometers. This study assumes a circular orbit of 500 kilometers. This limitation is selected in order to keep the structure below the Van Allen Radiation Belts. At the present time, materials being considered for expandable space structures make it impractical to operate in the Van Allen Belts. This fact is a result of the thickness of material required to protect the astronauts from the radiation encountered in these belts. The orbit parameters used in this study are shown in Table I.

In order for man to sustain life, he must have a partial pressure of oxygen of at least 3.0 lb/in^2 . However, an environment of 100% oxygen at 3.0 lb/in^2 is not considered practical because of the potential fire hazard associated with a pure oxygen environment. Mr. D. A. Rosenbaum, a physiologist with the Aerospace Medical Research Laboratory, suggests that an artificial environment be used which would afford the astronauts a partial pressure of oxygen of 3.5 lb/in^2 and a partial pressure of nitrogen of 4.0 lb/in^2 . This would give a total

Table I

Orbit Parameters

Parameter	Value
Eccentricity	1
Inclination	15°
Altitude	500 km
Regression	0
Rotation	0

internal pressure of 7.5 lb/in^2 and a gaseous environment consisting of approximately 40% by volume of oxygen and 60% by volume of nitrogen. In the analysis of a pressure vessel, a safety factor of 2 is normally employed. Therefore, in the structural analysis an internal pressure of 15 lb/in^2 is used.

Protection of the astronauts from the effects of the space environment is an obvious design criterion. The design of the composite wall is such that the wall will afford the astronauts all the protection that is necessary for their safety. In other words, it is assumed that the space suit is not necessary for any environmental protection and is worn only as a backup safety device.

The length of time a structure spends in space is an important factor in the analysis of the probability of meteoroid penetration and of the effect of the space environment on the materials. The life expectancy of the hangar is arbitrarily selected as one year.

Issues

This feasibility study begins with an investigation of the environmental effects on the materials and their mechanical properties. This investigation involves the environmental effects of meteoroids, radiation, vacuum, and temperature. Then, a composite wall is analyzed to determine the thickness required for radiation and

meteoroid bombardment protection, for low gas permeability through the wall, and for ability to perform as a pressure vessel. The analysis is made on a cylinder with hemispherical ends, the geometry of which is shown in Figure 4 on page 59. Finally, a wall design is proposed, conclusions are drawn, and recommendations for further study are made.

III. Selection of Materials

Introduction

A review of the literature revealed that some data is available on the environmental effects of meteoroids, radiation, vacuum, and temperature on materials proposed for expandable structures. With information available at the present time, the materials selected and analyzed in this study are considered by the writer to be the most promising of the various materials proposed for use in expandable-type structures. The materials used in the design of a composite wall for an expandable space hangar are polyester terephthalate, polyurethane foam, 181 style glass cloth reinforced polyester, 181 style glass cloth (urethane resin moisture cured), and polyvinylidene chloride. Each material performs a specific task or tasks in the protection of the inhabitants from the space environment. The purpose, behavior, and selection of each material is discussed in detail in subsequent sections.

Experimental investigations have been carried out on proposed expandable materials, such as those by Wolcott (Ref 2), Muraca et al. (Ref 14), and Jaffe and Rittenhouse (Ref 8). Most of these investigators consider only a specific material or a composite of two materials and the investigator is concerned with the behavior of the material

with respect to only one environmental aspect and neglects the others. In other words, investigators have yet to consider the interaction of radiation, vacuum, and temperature and the possible acceleration of degradation processes because of the interaction. The resulting reports, although useful in determining whether or not certain materials should be considered for possible use in space structures, fail to present quantitative results as to the effects of the space environment on the materials.

Wolcott (Ref 2:250) says about his investigation, "The test chamber employed for tests does not represent the space environment." Furthermore, the materials contained in a composite wall will in all probability perform better than when tested alone because they are part of a composite wall and are not exposed to the space environment as individual components. The outer surface of course, being exposed directly to the space environment, can be investigated as an individual component.

Effects of Vacuum

Most of the organic materials proposed for use in spacecraft are long-chained polymeric compounds which degrade in a vacuum not by evaporation or sublimation but by the breakdown of compounds into smaller more volatile fragments. This decomposition takes place not only at the surface but throughout the volume of the compound. Because the molecular weight of these fragments is not well

established, it is necessary to turn to direct experimental studies of the weight loss of polymers in a vacuum.

Jaffe and Rittenhouse (Ref 8:10) indicate that the rates of decomposition of polymers in a vacuum are often greatly accelerated by small amounts of impurities and addition agents. In other words, when the catalysts, which are ordinarily used to induce polymerization of a monomer, are left in the polymer, they commonly catalyze the decomposition of the polymer. Many polymers can be made without catalysts or the catalysts removed after polymerization, but the procedures are difficult and are not the commercial practice. Plasticizers and mold lubricants, employed to aid in the fabrication and to modify mechanical properties, are also highly detrimental to the stability of polymers in a vacuum. Obviously, the particular forming and curing procedure used in the manufacture of a polymer may have important effects on the stability of the polymer in a vacuum. Consequently, wide variations in behavior may be expected for any particular type of polymer. Experiments are needed to determine the stability of particular polymers which have been formulated and cured in a specific manner.

It is possible, in principle, for internal chemical changes to occur in organic materials when they are exposed to a vacuum which would affect the properties of the materials without significantly changing the weight of the

materials. When weight loss occurs, it may be accompanied by significant changes in mechanical properties. There is very little quantitative data available on these changes. If detailed information on a particular property of a particular material is required, it is usually necessary to test the material experimentally. In general, it may be said that weight losses of 1 or 2% do not produce property changes of engineering importance, but that weight losses of 10% are accompanied by significant changes in engineering properties. In a letter from Mr. Nels S. Hanssen of the GCA Viron Division (see Appendix D), Mr. Hanssen said that the vacuum of space is not expected to significantly change the engineering properties of the materials used in this study since they are all of very high molecular weight and have very low vapor pressures.

Effects of Meteoroids

The behavior of materials in space may be affected not only by the vacuum but also by the presence of particles which impinge on the materials. There are two possible effects of hypervelocity impacts which must be considered. The hypervelocity impacts of meteoroids can puncture or can lead to spallation of the vehicle wall and these impacts can result in the loss of internal air pressure. This problem is discussed and analyzed in Chapter IV of this study. Second, the hypervelocity im-

pacts of micro-meteoroids can also cause an erosion of the exterior surface. Jaffe and Rittenhouse (Ref 8:57) conclude that this will have negligible effects on the engineering properties.

Effects of Radiation

When atoms or ions with energies ranging from about 10 ev to about 1 Mev strike a solid surface, they tend to knock atoms off the surface. This process is defined as sputtering and may increase the loss over that occurring in a vacuum. There are major uncertainties both as to the flux of atomic particles to which a spacecraft will be exposed and the rates of sputtering for a given flux of particles. For a low earth orbit, Jaffe and Rittenhouse (Ref 8:31) conclude that the effect of sputtering is completely negligible. The principle effect of sputtering will be to degrade the surface coatings. The presence of ionized particles raises questions about the longevity of certain coatings, especially thin films of the softer materials. Data and information on actual conditions and the effects on materials is lacking.

Radiation can produce substantial changes in the mechanical and physical properties of expandable-type materials. These materials are generally susceptible to cross-linking or chain scission degradation.

In general, polyester terephthalate crosslinks and becomes more brittle when exposed to ultraviolet radiation.

Initially, the tensile strength increases slightly. In addition to the flexibility and high tensile and burst strength, polyester terephthalate is preferred for spacecraft use because of its inherent stability when exposed to space radiation. For prolonged exposures in space, polyester terephthalate requires some type of protection from the damaging effects of ultraviolet radiation. Normally such protection is provided by a vacuum deposition of an extremely thin layer of an ultraviolet reflector such as aluminum. The Expandable Structures Design Handbook (Ref 5:4-62) suggests that although polyester terephthalate is affected by ultraviolet radiation, the problem can be eliminated by the use of a vapor-deposited aluminum coating on the exterior surface. In a personal letter (see Appendix D), Mr. Nels S. Hanssen said that polyester terephthalate is considered a very stable material when exposed to space radiation. This fact is evidenced by the excellent performance of the Echo satellites.

There is no specific information available on the radiation effects on polyurethane foam; however, in a personal letter (see Appendix D), Mr. Nels S. Hanssen pointed out that an isocyanate-based elastomeric material has the best radiation resistance of 10 common elastomers. Since the urethane linkage is present in both the foam and the elastomer, the inference is made that the foam will behave in a similar manner. Therefore, polyurethane foam

is not expected to degrade significantly in a radiation environment.

Since the radiation resistance of organic polymeric materials such as epoxies, polyesters, and phenolics is greatly enhanced by fiberglass reinforcement, it is expected that 181 style glass cloth, an inorganic material, will perform satisfactorily in a radiation environment. Since the urethane linkage performs satisfactorily while exposed to radiation, 181 style glass cloth (urethane resin moisture cured) is expected to perform satisfactorily.

Polyvinylidene chloride decreases in tensile strength under gamma radiation which indicates chain scission. In a personal letter (see Appendix D), Mr. Nels S. Hanssen pointed out that investigators have found that polyvinylidene chloride darkens and loses all tensile strength at about 5×10^8 rads (1 Rad = 100 ergs/gm). He also pointed out that hydrogen chloride gas is evolved during degradation of this polymer.

Effects of Temperature Variation & Extremes of Temperature

In general, the effect of elevated temperature is to decrease the strength of expandable materials. Therefore, thermal control must be applied to the structure. In the environment of space, a spacecraft exchanges thermal energy with its surroundings exclusively by thermal radiation. In this study, the space thermal environment

is assumed to be composed of emission of radiation from the sun and earth and reflection of radiation from the earth. Neglecting any on-board power dissipation, the temperature of a spacecraft is dependent upon the thermal radiation interchange between the vehicle and the energy sources.

The Expandable Structures Design Handbook (Ref 5:3-85) suggests that for a 500 kilometer-circular orbit, the approximate temperature range is 200F to -100F but with judicious selection of a surface coating the temperature range can be reduced to 100 to 150F. The Expandable Structures Design Handbook (Ref 5:3-85) also points out that this temperature range will present no problem to the expandable materials. Since the major heating source is solar radiation, a high-emissivity coating is necessary. From experiments performed by Duft (Ref 4:522), Duft suggests that one approach is to provide an aluminized outer surface. This can be accomplished by using aluminized polyester terephthalate as the external surface of the composite wall. It is, therefore, concluded that temperature will have no significant effect on the material properties of the materials considered in this study.

Discussion

Investigators have determined generally what materials will show the least degradation when exposed to various

environments simulating the radiation, vacuum, or temperatures of space. Of course, the interaction of temperature, radiation, and vacuum will in all probability tend to accelerate the degradation processes. Until more comprehensive experimental studies are made and on the basis of experience with such satellites as those of the Echo series, it can only be assumed that the space environment will have negligible detrimental effects on the engineering properties of the selected materials over the one year time period considered in this study. It can generally be anticipated that these materials when placed in a composite wall will not degrade as rapidly as they would if they were exposed to the space environment individually.

Based on a review of available data, it was decided that the following materials can be expected to perform satisfactorily in an expandable space maintenance hangar:

- (1) Polyester terephthalate
- (2) Polyurethane foam
- (3) 181 style glass cloth reinforced polyester
- (4) 181 style glass cloth (urethane resin moisture cured)
- (5) Polyvinylidene chloride

IV. Meteoroid Shielding

Introduction

Although the meteoroid hazard has not been adequately evaluated for the optimum design of spacecraft in an earth orbit, a meteoroid environment may be estimated based on astronomical observations and explorations of near-earth space. Data obtained from Explorer VIII (Ref 12) and Explorer XVI (Ref 7) indicates that the flux of the more massive particles may be less than previously estimated.

The expandable wall concept has excellent potential for meteoroid protection because of its layered or composite construction. Each successive layer performs a function in preventing meteoroid penetration to the inner tension-carrying and pressure-retaining layers. The outer layer serves as a meteoroid bumper with the function of fragmenting the incoming meteoroid. The foam core helps to absorb the fragments and dissipates the shock wave caused by impact. The mechanism of stopping the particles in the foam involves fanning or coning action. The fragmented particles are divided into two groups, the faster group and the slower group. The foam core is designed to absorb the faster group and the inner facing is designed to stop the slower group.

Meteoroid Environment

The term meteoroid as used in this study includes all the minute solid particles that travel at high velocities in space. Two possible effects of hypervelocity impacts must be considered. First, the hypervelocity impacts of meteoroids can puncture or can lead to spallation of the vehicle wall. The larger meteoroid particles that have sufficient energy to penetrate a structure can lead to explosive decompression and damage to equipment. Second, the hypervelocity impacts of small meteoroids can cause erosion of the exterior surface. Jaffe and Rittenhouse (Ref 8:57) conclude that the amount of this type of erosion expected is so small that the effect, if any, on engineering properties is limited to the degradation of optical properties of exposed lenses, mirrors, and windows. Furthermore, this constant bombardment of small particles can affect the thermal balance of the structure.

Several investigators have attempted to define the meteoroid environment, but their results differ by orders of magnitude. Purser, et al. (Ref 15:83) state that the meteoroid environment being used by the Manned Spacecraft Center is shown in Figure 1 and is based on the expression

$$\text{Log } N = -1.34 \text{ Log } m - 10.423 \quad (1)$$

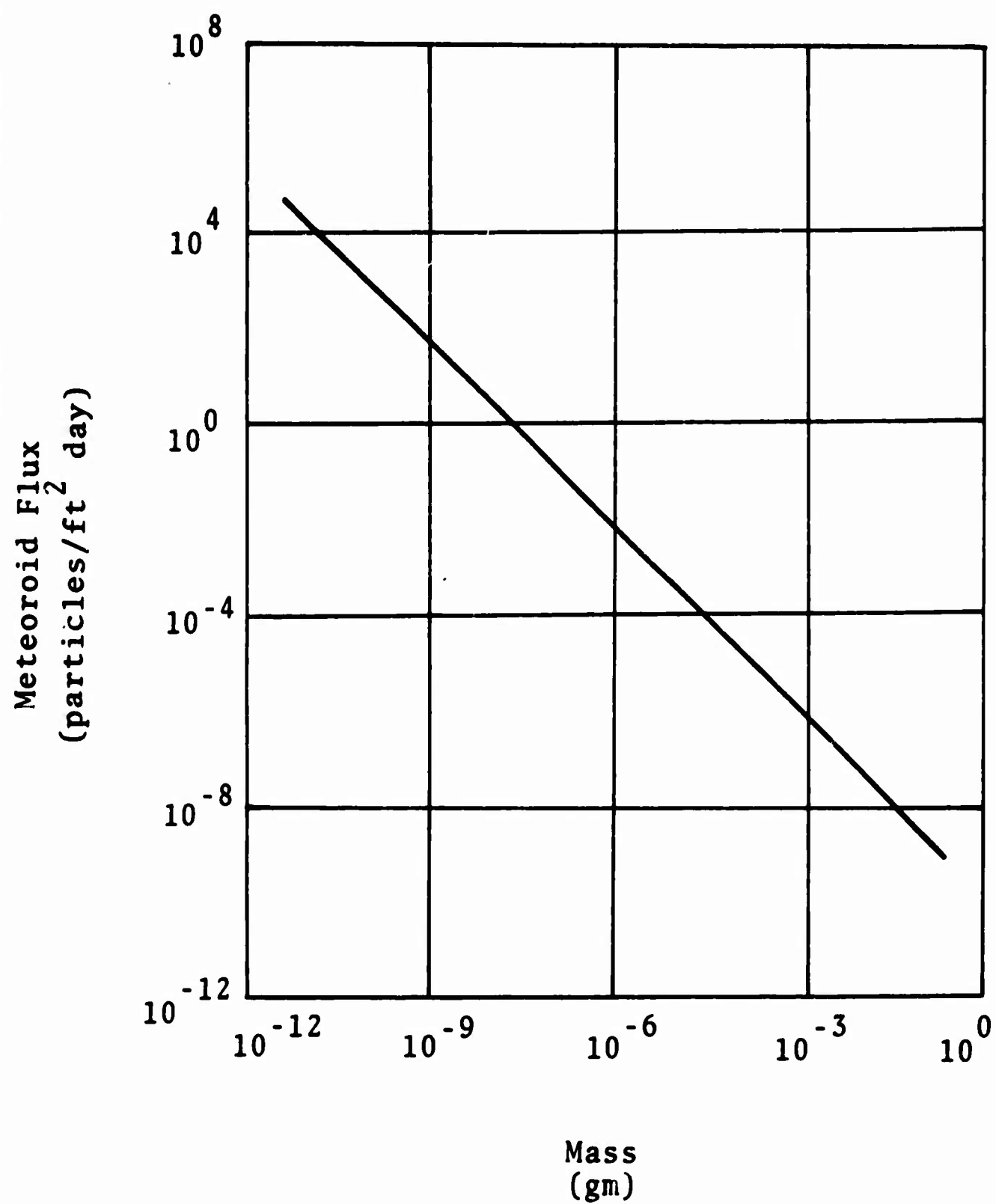


Fig. 1

Flux-mass Relationship of Meteoroid Environment

(Ref 14:83)

where

N = Meteoroid flux (particles/ft² - day)

m = Mass (gm)

The meteoroid flux (N) to be used in design is determined from probability theory. When the designer takes the probability of a single penetration in a single impact as being very small, the number of impacts he must consider in his calculations is very large and consequently, the mass of the critical meteoroid is large. A critical meteoroid is defined as the largest meteoroid which must be stopped by a wall in order to assure a given probability of no penetrations. Purser, et al. (Ref 15:59) suggest that for a probability of no penetrations, the following expression can be used:

$$\text{Log } P(0) = -0.434 N A T s \quad (2)$$

where

$P(0)$ = Probability of no penetrations

N = Meteoroid flux (particles/ft² - day)

A = Surface area of the structure (ft²)

T = Time in orbit (days)

s = Planetary shielding factor

The planetary shielding factor, s , is defined as

$$s = (1 + \cos \phi)/2 \quad (3)$$

where

$$\sin \phi = R/(R + H)$$

R = Radius of shielding body

H = Altitude above surface of shielding body

After selecting a desired probability of no penetrations, one can use equation (2) to determine the meteoroid flux (N) to be used in a design. Then using equation (1), one can determine the mass of the critical meteoroid.

Meteoroid Penetration Formulas

Many empirical penetration equations, developed in the literature, require a Brinell Hardness Number. Brink, et al. (Ref 2:184) suggest penetration formulas which are based on the target strength. These formulas and their applicable velocity ranges are

$$\underline{V = 10,000 \text{ ft/sec}}$$

$$t'_p = 1.5(0.172) V^{0.893} \rho_m^{0.979} S_t^{-0.457} \rho_t^{-0.35} \bar{V}_m^{0.33} \quad (4)$$

$$\underline{V = 20,000 - 30,000 \text{ ft/sec}}$$

$$t'_p = 1.5(0.772) V^{0.449} \rho_m^{0.673} S_t^{-0.275} \rho_t^{-0.426} \bar{V}_m^{0.33} \quad (5)$$

$$\underline{V = 65,000 - 80,000 \text{ ft/sec}}$$

$$t'_p = 1.5(0.97) V^{0.21} \rho_m^{0.39} S_t^{-0.10} \rho_t^{-0.46} \bar{V}_m^{0.33} \quad (6)$$

$$V = 100,000 - 240,000 \text{ ft/sec}$$

$$t'_p = 1.5(0.97) V^{0.18} \rho_m^{0.26} S_t^{-0.04} \rho_t^{-0.46} \bar{V}_m^{0.33} \quad (7)$$

where

t'_p = Penetration depth in a thin plate (in)

V = Velocity of meteoroid or fragment of meteoroid
(ft/sec)

ρ_m = Density of meteoroid or fragment of meteoroid
(lb/in³)

S_t = Shear yield stress of target material (lb/in³)

ρ_t = Density of target material (lb/in³)

\bar{V}_m = Volume of meteoroid or fragment of meteoroid (in³)

Because the Brinell Hardness Number would be difficult to obtain for the types of materials considered in this study, the equations (4) through (7) are used because they are based on the target strength and not on a Brinell Hardness Number.

Analysis

The first step in the design of a composite wall for meteoroid protection was the determination of the critical meteoroid and its properties. Equations (1), (2), and (3) were employed in this determination and the results are presented in Table II. Appendix A gives a sample calculation of the properties of a critical meteoroid using a

Table II
Some Critical Meteoroid Properties

NOTE: P(O) = Probability of no penetrations

Property	Symbol	Value		
		P(O) = 0.990	P(O) = 0.995	P(O) = 0.999
Mass (lb)	m_m	3.24×10^{-5}	5.30×10^{-5}	1.93×10^{-4}
Density ^a (lb/in ³)	ρ_m	7.25×10^{-2}	7.25×10^{-2}	7.25×10^{-2}
Volume (in ³)	V_m	4.46×10^{-4}	7.35×10^{-4}	2.66×10^{-3}
Diameter (in)	D_m	9.49×10^{-2}	1.12×10^{-1}	1.72×10^{-1}
Velocity ^a (ft/sec)	V_m	1.00×10^5	1.00×10^5	1.00×10^5
Shear Yield Stress ^b (lb/in ²)	S_m	1.00×10^4	1.00×10^4	1.00×10^4
Shape ^c		Sphere	Sphere	Sphere

^aRef 3:10

^bAssumed for glasslike material (Ref 1:64)

^cRef 2:198

probability of no penetrations equal to 0.999.

The analysis of the composite wall for meteoroid protection is based on a method previously developed and used by Thompson (Ref 2:198-201). The thicknesses and weights of the composite wall and of the components used in the composite wall are shown in Table III and Table IV. Appendix B gives a sample calculation of the thickness and weight necessary for meteoroid protection and is based on a probability equal to 0.999.

Discussion

The obvious conclusion reached from a review of the literature is that there is a hazard to space flight because of the possibility of meteoroid impacts but only very crude estimates of this hazard can be made at present. Space experiments on the damage caused by meteoroids are presently being conducted, and a comprehensive evaluation of these experiments will give a designer of future spacecraft more exact information on design criteria. At present, the study of hypervelocity impact presents two very formidable obstructions to the spacecraft designer. The first problem is the inability of experimenters to obtain velocities in the range of interest (40,000 to 200,000 ft/sec) with particles of known mass and dimensions. The second problem is the inability of experimenters to agree on the damage to be expected even in the velocity region now under investigation (up to 20,000 ft/sec). The

Table III
Thickness of Wall Components for Meteoroid Protection

NOTE: P(O) = Probability of no penetrations

Wall Component	Material		Thickness (in)	
		P(O) = 0.990	P(O) = 0.995	P(O) = 0.999
Outer Facing	181 Style Glass Cloth	0.100	0.118	0.183
Core	Polyurethane Foam	0.227	0.267	0.409
Inner Facing	Polyester Terephthalate	0.128	0.151	0.230
Total Wall	Composite	0.455	0.536	0.822

Table IV
Weight of Wall Components for Meteoroid Protection

NOTE: P(O) = Probability of no penetrations

Wall Component	Material	Weight (lb/ft ²)		
		P(O) = 0.990	P(O) = 0.995	P(O) = 0.999
Outer Facing	181 Style Glass Cloth	1.320	1.560	2.410
Core	Polyurethane Foam	0.038	0.045	0.057
Inner Facing	Polyester Terephthalate	0.877	1.046	1.579
Total Wall	Composite	2.235	2.651	4.046

analysis used in this investigation has yet to be confirmed experimentally.

Table II shows the influence that the probability of no penetrations has on the properties of the critical meteoroid. As the probability of a meteoroid penetrating the structure decreases, the size of the critical meteoroid with which the designer has to contend increases. Table III and Table IV show the influence that the probability of no penetrations has on the thickness and weight of the wall design. As the probability of a meteoroid penetrating the structure decreases thereby increasing the size of the critical meteoroid, it follows that the thickness and weight of the composite wall needed to stop the larger meteoroid increases. For a probability of no penetrations of 99.0%, the thickness and weight of the composite wall are 0.455 inches and 2.235 lb/ft^2 respectively. If the designer desires a probability of 99.5%, the thickness of the composite wall increases by only 0.081 inches and the weight increases by only 0.416 lb/ft^2 . However, if the designer desires to increase the probability from 99.5% to 99.9%, the thickness increases by 0.286 inches and the weight increases by 1.395 lb/ft^2 . Almost all design problems are characterized by compromises. However, this writer concludes that the additional weight associated with the probability of 99.9% is warranted and, therefore, concludes that the composite wall design associated with a probability of no penetrations of 99.9% be used.

V. Radiation Shielding

Introduction

One of the most important environmental factors which influences many aspects of manned space flight is the presence of tissue-damaging radiation. This radiation is a result of high-energy particles whose fluxes and energies vary over several orders of magnitude. In addition to the very large flux variation, the spatial distribution of this radiation is such that certain regions present much greater peril for the astronaut than do other locations. The degree of protection necessary against this radiation is a function of the astronauts' time in space and the type, quantity, and energy of the radiation encountered during a given mission. This section is divided into three parts. The first part presents a brief account of the mechanism of interaction between radiation and matter. The second part presents a description of the intensity and extent of trapped radiation environment and a description of the very serious problem posed by solar flares. The third part presents an analysis of the shielding requirements necessary for an expandable space hangar.

Interaction of Radiation with Matter

Radiation encountered in space can be classified as particulate radiation and as electromagnetic radiation. Both of these can be discussed in terms of mass-energy and momentum attributes, but in their interaction with matter, they manifest distinctly dissimilar properties. Particle radiation is based on the corpuscular nature of the electron and the proton. Electromagnetic radiation is based on the electromagnetic nature of the photon.

The Electron. The electron, because of its electric charge, reacts with other constituents of matter, including other electrons, through its electric field. Depending upon its energy and the atomic number of the material through which it passes, the electron gradually dissipates its energy through the processes of excitation, ionization, elastic scattering, and bremsstrahlung production. Electrons in the energy range up to approximately 10 Mev dissipate their energy in matter primarily in two ways. First is the loss of energy through the process of excitation and ionization with the bound electrons of the atoms of the material. This is known as ionization energy loss and is the dominant means by which an electron dissipates its energy as it traverses a material absorber. Secondly, the incident electrons can be deflected and decelerated by the electric field of the atomic nucleus and in the process emit electromagnetic radiation known as

bremsstrahlung. The bremsstrahlung photons thus produced have a very broad spectral distribution and those of higher energy have great penetration power.

The Proton. Protons and other heavy charged particles, with energies in the range of 10 Mev to 1 Bev, lose energy almost exclusively by inelastic collisions with the atomic electrons of the material through excitation and ionization. This causes a practically continuous reduction of energy as the protons penetrate the target material. The distance which a proton penetrates matter is dependent on its kinetic energy and the atomic number of the material. Younger et al. (Ref 21:172) point out that the lower the atomic number the less mass of material is required to attenuate the protons. Consequently, within other constraints such as bulk, toxicity, deterioration, etc., the use of low atomic number materials whenever possible results in a significant overall advantage with respect to boost-weight penalty.

The range-energy relations do not consider the nuclear collisions to which the incident protons are subjected as they traverse material structures. Considering the energies of the Van Allen Belt and solar flare protons, these interactions result generally in the production of secondary neutrons and protons. Because the neutrons are electrically neutral, they do not lose energy by ionization and hence may penetrate to the interior of the vehicle and contribute

to the radiation field whereas the initiating proton may be energetically incapable of penetration.

The Neutron. Because neutrons are released by the interaction of proton bombardment on a shielding material, they present a radiation hazard. High energy neutrons passing through a shielding material are slowed down and absorbed by the material or are scattered and diffused out of the material. The loss of the neutron's kinetic energy is accomplished by elastic and inelastic collisions with the nuclei of the shielding material. In an elastic collision there is merely an exchange of kinetic energy at the expense of the neutron. For this reason, the lighter-shield nuclei are best because for low atomic number materials, elastic collisions quickly neutralize the high-energy neutrons. However, in an inelastic collision, the neutron dissipates its energy not only through kinetic energy transfer, but also through the excitation of the struck nucleus. This latter process for the dissipation of energy is the primary manner in which neutrons lose their energy and as a result of this excitation, energy is then released as one or more photons.

The Photon. Except for the manner by which photons originate and the differences due to the classification with respect to their frequencies, bremsstrahlung, X-rays, and gamma rays are all photons of electromagnetic energy and subject to the same attenuation processes. When

referring to the interactions of electromagnetic quanta, these three terms may be used interchangeably. Because the number of photons removed is dependent upon the thickness traversed and the composition of the target material and also upon the number incident on the material, the decrease in the intensity of a photon beam follows an exponential pattern with respect to the distance that a photon beam travels in the target material.

There are primarily three distinct methods by which a photon may react with matter and thereby transfer all or part of its energy to the target material. These three methods are photoelectric absorption, Compton scattering, and pair production. The relative importance of each of these means of attenuation varies widely depending upon the energy of the photon and the material with which it reacts. Below approximately 0.1 Mev for low \bar{Z} (atomic number) materials, the predominant reaction is the complete absorption of the photon by an electron. This is known as photoelectric effect. Up to about 2 Mev, photon attenuation is caused by the Compton effect while between 2 Mev and 20 Mev pair production becomes essentially the only way for photons to vanish. The Compton effect is a process in which an incident photon collides with a free electron and is deflected with a corresponding loss of energy. Pair production occurs when a photon is absorbed in the strong electric field that surrounds a nucleus and an

electron-positron pair is created.

Environmental Considerations

Van Allen Belts. The geomagnetic field of the earth provides suitable conditions for confining charged particles within the vicinity of the earth. This volume of charged particles, symmetrical about the geomagnetic equator, contains protons and electrons and is known as the Van Allen Radiation Belts. The inner or proton belt starts at 800 to 1000 kilometers above the surface of the earth and extends out to about 15,000 kilometers from the center of the earth. The peak intensity of this belt is located at approximately 10,000 kilometers from the center of the earth and is a belt which is approximately perpendicular to the earth's geomagnetic axis. The outer or electron belt contains primarily electrons of large fluxes and high energies. Some protons have been detected in the outer belt but they are of low energies. No high energy protons have been detected as contributing to this field. The volume of geomagnetically trapped electrons starts at about 10,000 kilometers and extends to about 60,000 kilometers from the center of the earth and ranges between 60 and 70 degrees north and south of the geomagnetic equator. The maximum intensity is located at about 23,000 kilometers from the center of the earth. These generally defined radiation belts are not of prime concern because this study assumes a circular orbit of 500 kilo-

meters. There exists, however, a magnetic anomaly located over the South Atlantic Ocean where the inner Van Allen belt descends to low altitudes, and which is of concern because an orbit of 500 kilometers will traverse this volume of trapped high-energy protons. Freden and Paulikas (Ref 6:1) state that fluxes of protons in the energy intervals from 5 to 20 Mev and 60 to 120 Mev have been detected in the South Atlantic Anomaly.

Solar Flares. Enormous increases in the intensity of the radiation field have been detected and correlated with the occurrence of flare phenomena on the surface of the sun. The frequency of occurrence of solar flares together with lack of reliable forecasting techniques make solar flare radiation one of the major obstacles to be considered in the design of a space vehicle. Because solar flare activity is apparently associated with sunspot activity, the maximum and minimum frequency values will vary in general with the eleven-year sunspot cycle. Several empirical relations have been proposed to fit observed data, but their value in predicting flare events is limited and obviously unsatisfactory for the purpose of establishing departure times for extraterrestrial missions. The amount of data pertaining to solar flare activity accumulated since the beginning of the International Geophysical Year (1 July 1957 to 31 December 1958) is far more complete and detailed than had been previously obtained.

Nevertheless, no reliable system has been devised for confidently predicting the occurrence of solar flare activity.

Because solar flares vary greatly in size, intensity, and their terrestrial effects, they have been classified in three groups. The classification is based on the optical area of the flare. Type 3 flares are those which may contain particles having the highest velocities, 0.1 to 0.3 times the velocity of light. These limits correspond to proton energies in the range of 5 to 50 Mev. A number of flares containing primary particles in excess of 15 Bev have been observed and have been classified as type 3+. Most of these flares have occurred during a period of increased solar activity with which the IGY was selected to correspond, and their frequency and intensity may conform to some solar cycle.

With respect to protons, the effect of type 1 and 2 flares can be discounted since the proton energies in these range from a few Kev to the order of 1 Mev. The protons associated with the type 3 flares do not exceed in energy those which are supposedly normally present in a 500 kilometer environment (see Table VII). However, the possibility of occurrence of type 3+ solar flares with associated proton showers must be considered, even though these events are relatively rare (averaging less than 1 per year). At the present time, it is impractical to

attempt to shield a structure of the space-maintenance-hangar size against the protons associated with the type 3+ flare. Therefore, it is suggested that a warning device be developed which would permit the astronauts time to enter a protective capsule. A maintenance schedule could also be constructed around probable high energy solar flare activity.

Also associated with solar flares is an increase in the X-ray intensity from the sun. Lampert and Younger (Ref 10:197) suggest that even though the flux may be great the photon energies are in the 1 to 10 kilovolt region and are easily absorbed by the vehicle walls.

Galactic Cosmic Radiation. Galactic cosmic radiation, also known as primary cosmic radiation, has a fairly homogeneous distribution throughout space. This type of cosmic radiation penetrates our solar system from other parts of the galaxy and is known to be non-directional as observed from the earth. Cosmic radiation's principle constituents are the hydrogen nuclei (proton - approximately 90 percent) and the helium nuclei (alpha particles - approximately 9 percent). High energy cosmic rays are isotropic and the intensity does not show a time variation, although a local source, such as the sun, will during intense activity, disrupt the quiescent uniformity because of changes in the local magnetic fields. Because the incident flux is extremely low, shielding against galactic

cosmic radiation is not necessary. Furthermore, because protons of primary cosmic origin are in the Bev energy-range, shielding against these protons becomes impractical because of large shielding mass required, and because energetic cosmic primaries initiate secondary radiation in the shield which is more damaging than the unshielded primary radiation.

Radiation Shielding

Radiation shielding can be catagorized as active shielding or passive shielding. Active shielding is a method by which the trajectories of the incident charged particles are altered in such a manner that they do not enter the space vehicle. The two types of active shielding are electromagnetic and electrostatic. The electromagnetic shielding is provided by means of a dipole-like magnetic field. This method makes use of superconducting coils which trap or deflect charged radiation-energy particles in the same way as the earth's magnetic field does. The electrostatic method involves a double-wall system in which the inner wall is given a positive voltage relative to the outer wall. Therefore, protons which have energies in electron volts less than the wall will not penetrate the inner wall. Passive shielding is a method by which the incident radiation is absorbed or deflected by the shielding material. In this investigation the method of passive shielding is employed.

The Average Man. In order to evaluate a design of a composite wall necessary for radiation protection for man, one must define the average man. It is assumed that the average man has a composition of water, has a weight of 165 lbs (7.5×10^4 gm), has a thickness of 50 cm, and has a surface area of $5 \times 10^3 \text{ cm}^2$ (Ref 10:179). An abundant amount of literature is available on the biological effects of ionizing radiation and, therefore, no attempt is made in this study to discuss or treat the general biological interactions of radiation on man. The criteria used in this study is that an average man may absorb 2 rads per day for several months and that he may absorb a maximum total allowable dosage of 200 rads. The Space Planners Guide (Ref 18:11-15) states that for missions of several months duration, the acceptable dose rate to the blood-forming organs of a man should not exceed 2 rads/day. This rate permits some recovery so that the total retained dose remains below a critical level.

Shielding Against Electrons. A 500 kilometer orbit traverses regions of high electron fluxes with energies up to 7 Mev. Table V gives the electron spectrum for a 500 kilometer orbit. This electron spectrum was furnished by the Air Force Weapons Laboratory and is based on the orbit parameters contained in Table I on page 8. The spectrum was computed using an IBM program with a data

Table V

Electron Spectrum for Assumed Orbit

NOTE: Information furnished by the Air Force Weapons Laboratory, Kirtland AFB, New Mexico

Energy (Mev)	Electron Flux (particles/cm ² -sec)	Incident Energy (Mev/cm ² - sec)
0.3 - 0.5	1.278	0.6390
0.5 - 1.0	2.130	2.130
1.0 - 1.5	2.113	3.160
1.5 - 2.0	1.762	3.524
2.0 - 3.0	0.138	0.414
3.0 - 4.0	0.1537	0.6148
4.0 - 5.0	0.0271	0.1355
5.0 - 6.0	0.0119	0.0715
6.0 - 7.0	0.00527	0.0368

deck furnished by Vetti. It should be noted from Table V that there appears to be a significant decrease in the flux and incident energy associated with the energies greater than the 2 Mev electron. The most significant fact of the electron spectrum is that approximately 88% of the incident energy is a result of electrons with energies equal to or less than 2 Mev. The Air Force Weapons Laboratory also furnished a total 10-day integrated flux based on the assumption that the flux is omnidirectional. This total flux is 7.00697×10^9 electron particles per square centimeter per 10 day period. Figure 2 shows the variation of range with energy for electrons in aluminum. Younger et al. (Ref 21:168) state that the range-energy curve for electrons incident on aluminum can be used with little error for other low Z (atomic number) materials. Because the average atomic number of polyester terephthalate is quite small, the fraction of the electron energy converted to bremsstrahlung is very small. In this study, the effect of bremsstrahlung is neglected.

Since the thickness required to completely stop an electron is given by

$$t = RE/\rho \quad (8)$$

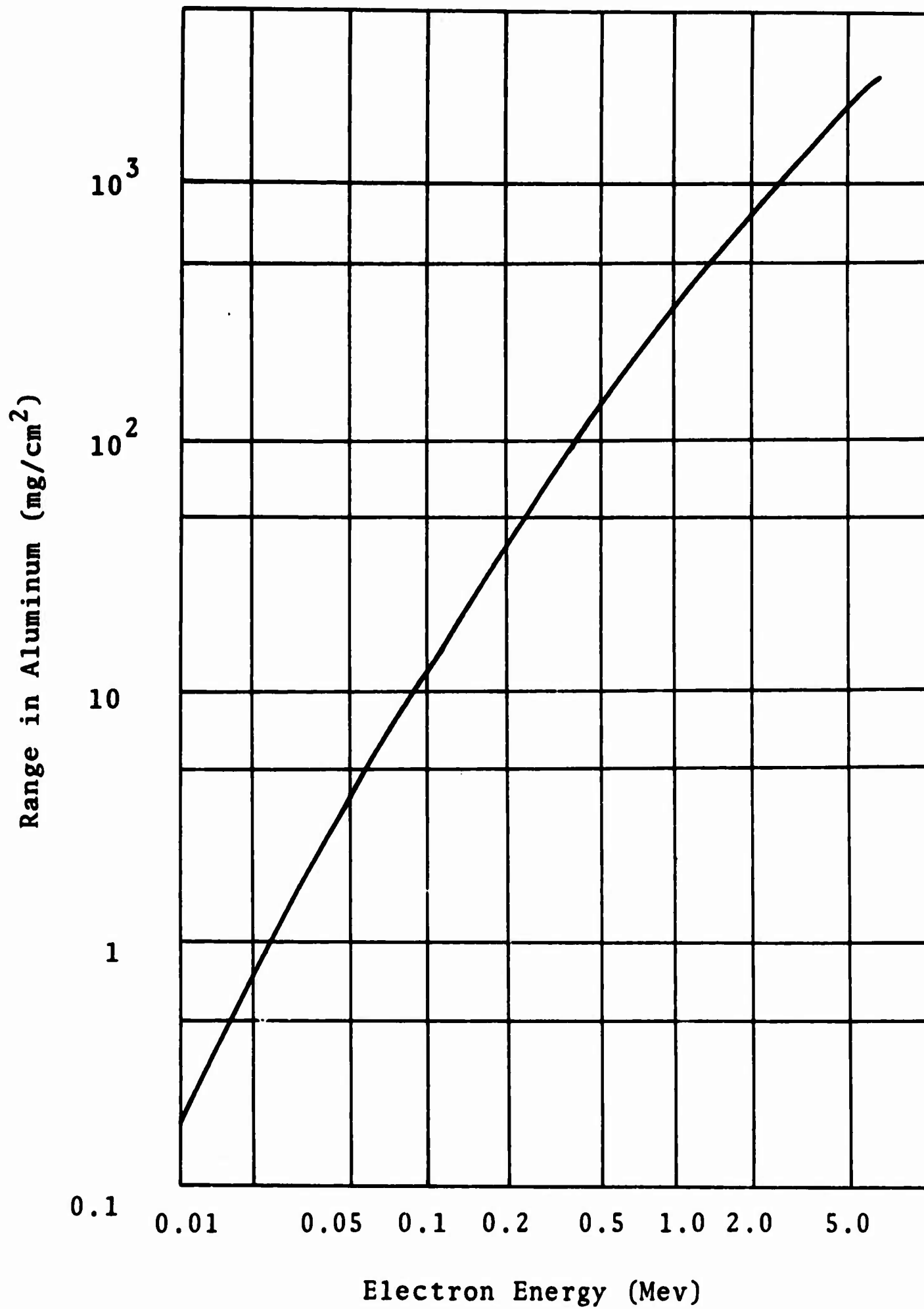


Fig. 2

Electron Ranges in Aluminum

(Ref 21:169)

where

t = Thickness (cm)

RE = Range-energy (gm/cm^2)

ρ = Density (gm/cm^3)

the thickness of polyester terephthalate necessary to completely stop a 2 Mev electron is approximately

$$t = 0.9/1.39 = 0.647 \text{ cm} = 0.255 \text{ in}$$

The 2 Mev electron is selected because of the fact that approximately 88% of the incident energy is below this electron energy level. It is well to remember at this point that in Chapter IV, it was found that 0.230 inches of polyester terephthalate is required for meteoroid protection based on a probability of no penetration of 99.9%.

For an extremely conservative design, assume that the electrons with energies in excess of 2 Mev do not lose any energy while passing through the 0.255 in of polyester terephthalate and that the electrons do not lose energy while traversing the artificial environment. In other words, the astronaut is exposed directly to an electron environment of energies greater than 2 Mev. From Table V, the incident energy above 2 Mev which impinges on an astronaut is $1.2726 \text{ Mev}/\text{cm}^2\text{-sec}$. This is equivalent to $6,363 \text{ Mev}/\text{sec}$ -average man or $10.2 \times 10^{-3} \text{ ergs}/\text{sec}$ -average man. Using the total integrated electron flux for

a 10 day period (7.00697×10^9 particles/cm²-10 days) and the weight of the average man (7.5×10^4 gms), the total electron incident energy on an average man per day is 12.5 ergs/gm-day-average man or 0.125 rads/day-average man. Therefore, it can be safely concluded that an astronaut who is shielded by a composite wall containing at least 0.255 in of polyester terephthalate will receive a radiation dose from electrons of not more than 0.125 rads/day.

Obviously, the composite wall, which also involves layers of foam and glass cloth, will afford an astronaut more protection than just the polyester terephthalate; however, this analysis shows that it is feasible to use a material such as polyester terephthalate for radiation protection against electrons.

Shielding Against Protons. Sternheimer (Ref 19:1045) gives an expression which may be used to determine the range-energy relations for protons in various substances provided an appropriate value of the average excitation and ionization potential I is used. The range of a proton with a kinetic energy T_p in a material whose average ionization and excitation is I , is given by

$$RE(T_p, I) = RE(2 \text{ Mev}, I) + (\bar{A}/2\bar{Z}) \phi_{A1}(T_p) G_{(9)}$$

$$\text{where } G = 1 + G_1 x + G_2 x^2 + G_3 x^3 \quad (10)$$

The values of the G_i and $\phi_{A1}(T_p)$ are tabulated in Table 1 of Ref 18:1047 and are functions of the proton kinetic energy. $\phi_{A1}(T_p)$ is determined using $I_{A1} = 166$ ev. Aluminum thus is used as the reference element from which the range-energy relations of the other materials are computed. The factor $\bar{A}/2\bar{Z}$ is derived from the original Bethe-Block expression giving the linear space rate of energy loss of the charged particle as it passes through matter. \bar{A} is the atomic weight and \bar{Z} is the atomic number of the material under consideration.

The additive constant, $RE(2 \text{ Mev}, I)$, is the range of a 2 Mev proton in the subject material and is obtained empirically. Younger, et al. (Ref 21:191) point out that for light elements, the additive constant has a value of approximately 0.01 gm/cm^2 and hence can be neglected in subsequent calculations.

The function x is defined as

$$x = \text{Log} (I/I_{A1}) = \text{Log} (I/166) \quad (11)$$

Equation (11) shows the dependence of the range-energy formula on the value of I . The exact value of I for a given substance must be determined experimentally although the ratio of I/\bar{Z} is a slowly decreasing function ranging from about 15.6 for hydrogen to about 8.8 for lead.

Younger, et al. (Ref 21:191) suggest the approximate value

of 13.5 for low \bar{Z} materials. The value of 13.5 is used in the computations.

From equations (9), (10), and (11), Table VI is constructed. Table VI shows the proton range in polyester terephthalate and an example calculation is shown in Appendix C. Table VII gives the proton spectrum for a 500 kilometer orbit. This proton spectrum was furnished by the Air Force Weapons Laboratory and is based on the orbit parameters contained in Table I on page 8. The Air Force Weapons Laboratory also furnished a total 10-day integrated flux based on the assumption that the flux is omnidirectional. This total flux is 5.30903×10^6 particles per square centimeter per 10 day period.

From Table VI, 0.905 gm/cm^2 of polyester terephthalate will stop all protons with energies of 30 Mev or less. Dividing by the density of polyester terephthalate, the thickness necessary to stop a 30 Mev proton is found to be approximately 0.255 in. Of course the protons with energies greater than 30 Mev lose some energy as they traverse the 0.255 in of polyester terephthalate; however, for this feasibility study, assume that protons with energies greater than 30 Mev do not lose any energy as they pass through the polyester terephthalate. The shield design problem can become very involved but for simplicity the assumption that protons greater than 30

Table VI

Proton Ranges in Polyester Terephthalate

Proton Energy (Mev)	Range in Polyester Terephthalate (gm/cm ²)
10	0.118
20	0.424
30	0.905
40	1.530
50	2.290
100	8.000
200	27.000
500	122.000

Table VII

Proton Spectrum for Assumed Orbit

NOTE: Information furnished by the Air Force Weapons Laboratory, Kirtland AFB, New Mexico

Energy (Mev)	Proton Flux (particles/cm ² - sec)	Incident Energy (Mev/cm ² - sec)
20-30	0.0942	2.8260
30-40	0.0628	2.5120
40-50	0.05714	2.8705
50-60	0.05096	3.0576
60-70	0.04524	3.1668
70-80	0.04016	3.2128
80-90	0.03566	3.2094
90-100	0.03166	3.1660
100-110	0.02810	3.0910
110-120	0.02494	2.9928
120-140	0.009538	1.33532
140-160	0.007674	1.22784
160-180	0.006539	1.17702
180-200	0.005572	1.14400
200-250	0.003735	0.93375
250-300	0.002504	0.75120
300-400	0.002803	1.08120
400-500	0.0012596	0.64980

Table VII (continued)

Energy (Mev)	Proton Flux (particles/cm ² -sec)	Incident Energy (Mev/cm ² -sec)
500-600	0.000566	0.33960
600-700	0.0002544	0.17808
700-800	0.00011427	0.091016
800-900	0.00005135	0.046215
900-1000	0.00002307	0.023070

Mev pass through the wall of the space hangar without any loss of energy is made.

It is now possible to calculate the energy absorbed by an occupant of the space hangar. From Figure 3, it is noted that the average man will absorb all protons with energies of 300 Mev or less. For the range of 30 Mev to 300 Mev, Table VII shows that the average man will absorb 33.84803 Mev/cm²-sec. From Table VIII for an energy range of 300 Mev to 1000 Mev, the total energy absorbed by an average man is 0.813957 Mev/cm²-sec. Therefore, the total energy from protons absorbed by an average man is 34.661987 Mev/cm²-sec. This is equivalent to approximately 173,310 Mev/sec-average man or 0.2775 ergs/sec-average man. Using the total integrated proton flux for a 10 day period (5.30903×10^6 particles/cm²-10 day) and the weight of the average man (7.5×10^4 gms), the total absorbed energy of an average man is 4.11 ergs/gm-day-average man or 0.0411 rads/day-average man. Therefore, it can safely be concluded that an astronaut who is shielded by a composite wall containing at least 0.255 in of polyester terephthalate will receive a radiation dose from protons of not more than 0.0411 rads/day.

Obviously, the composite wall will afford an astronaut more protection; however, from this analysis, it is apparent that a material such as polyester terephthalate can be used as a radiation shield against protons. For

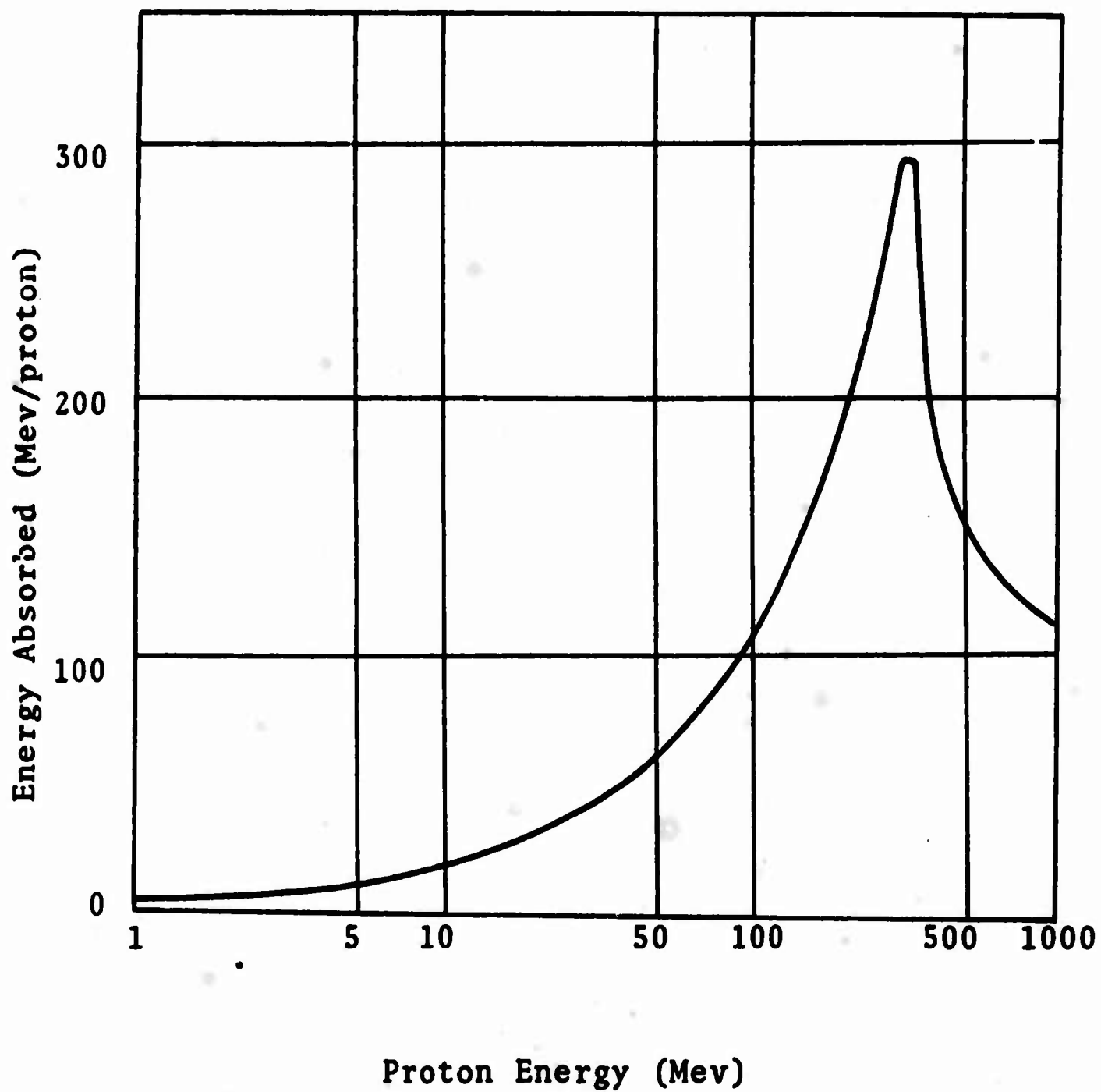


Fig. 3

Total Energy Absorbed Per Proton by an Average Man

(Ref 17:184)

Table VIII

Incident Energy Absorbed by an Average Man

Proton Energy (Mev)	Energy Absorbed (Mev/proton)	Incident Energy Absorbed (Mev/cm ² - sec)
300-400	175	0.490525
400-500	150	0.188940
500-600	140	0.079240
600-700	130	0.033072
700-800	120	0.0137124
800-900	115	0.005929
900-1000	110	0.0025377

the assumed orbit, the protons with energies greater than 20 Mev do not appear to be a significant factor in radiation protection.

Shielding Against Neutrons. Information available at the present time regarding the neutron flux above the earth's atmosphere indicates that it is so small that no hazard is expected and consequently no shielding for this type of radiation is required. The earth's atmosphere is regarded as the predominant source of these neutrons.

Shielding Against Photons. Infra-red and gamma rays are very difficult to shield against. However, their effects are not particularly deleterious because of their small fluxes. Since X-rays from the sun are of such low energy, the hazard from electromagnetic radiation exists only if the skin is exposed directly to these soft X-rays. Consequently, almost any thin sheet of material between an astronaut and the sun serves as an effective X-radiation shield.

Discussion

Even though the energies of electrons are much lower than the energies of protons, the enormous flux of the electrons makes them the primary radiation hazard for a circular orbit of 500 kilometers. Because at least 0.230 inches of polyester terephthalate is needed for meteoroid protection ($P(0) = 0.999$) and because 88% of the electron

incident energy is associated with electron energies equal to or less than 2 Mev, the 2 Mev electron is selected as the energy level to be stopped by the polyester terephthalate.

With 0.255 in of polyester terephthalate, the total radiation to which an astronaut will be exposed is not more than 0.1661 rads/day. The composite wall will afford an astronaut more protection. However, this study and analysis shows that it is not only feasible to use a material such as polyester terephthalate for radiation protection but also extremely practicable when considering a space structure of the space-hangar size. With an average dose of 0.1661 rads/day, an astronaut could spend well over a year in the space hangar and still remain below the accumulative dose of 200 rads. However, it must be remembered that the astronauts will be leaving and entering the hangar as they perform their primary tasks of space maintenance. Furthermore, other items such as reliability of performance and human factors will be the limiting criterion in the amount of time an astronaut is able to spend assigned to the maintenance hangar.

VI. Pressure Vessel

Engineering Properties

The load carrying member of the composite wall is 181 style glass cloth (urethane resin moisture cured). The urethane resin is that developed under contract Nr AF 33 (657)-10409. From tests conducted by Rochon, et al. (Ref 16:112), the ultimate stress of 181 style glass cloth is 26,700 lbs/in². Mr. Thomas L. Graham of the Elastomers Branch of the Air Force Materials Laboratory suggests that for a conservative design an ultimate stress of 26,000 lbs/in² should be used. Mr. James Whittney, the Senior Project Engineer of the Plastics and Composite Branch of the Air Force Materials Laboratory, suggests that a Young's Modulus of 5×10^6 lb/in² and a Poisson's Ratio of approximately 0.3 be used for 181 style glass cloth (urethane resin moisture cured). These values are conservative enough to allow the assumption that the glass cloth acts as an isotropic material.

Membrane Analysis

Because the radius (r) is much greater than the thickness (t), the membrane theory is employed in the structural analysis. Although membrane analysis alone is inadequate for analyzing the joints between the cylindrical portion and the hemispherical ends of the vessel, certain

assumptions can be made in order to obtain an approximate solution to the problem.

In the case of a cylindrical vessel with hemispherical ends (Fig. 4), the stresses acting at a sufficient distance from the joints ab and a'b' are from membrane theory

$$\sigma_x = pr/2t \quad (13)$$

$$\sigma_t = pr/t \quad (14)$$

For the hemispherical ends, the membrane theory gives a uniform tensile stress

$$\sigma = pr/2t \quad (15)$$

where for equations (13), (14), and (15)

σ_x = Stress in x direction (lb/in²)

σ_t = Stress in tangential direction (lb/in²)

σ = Uniform tensile stress (lb/in²)

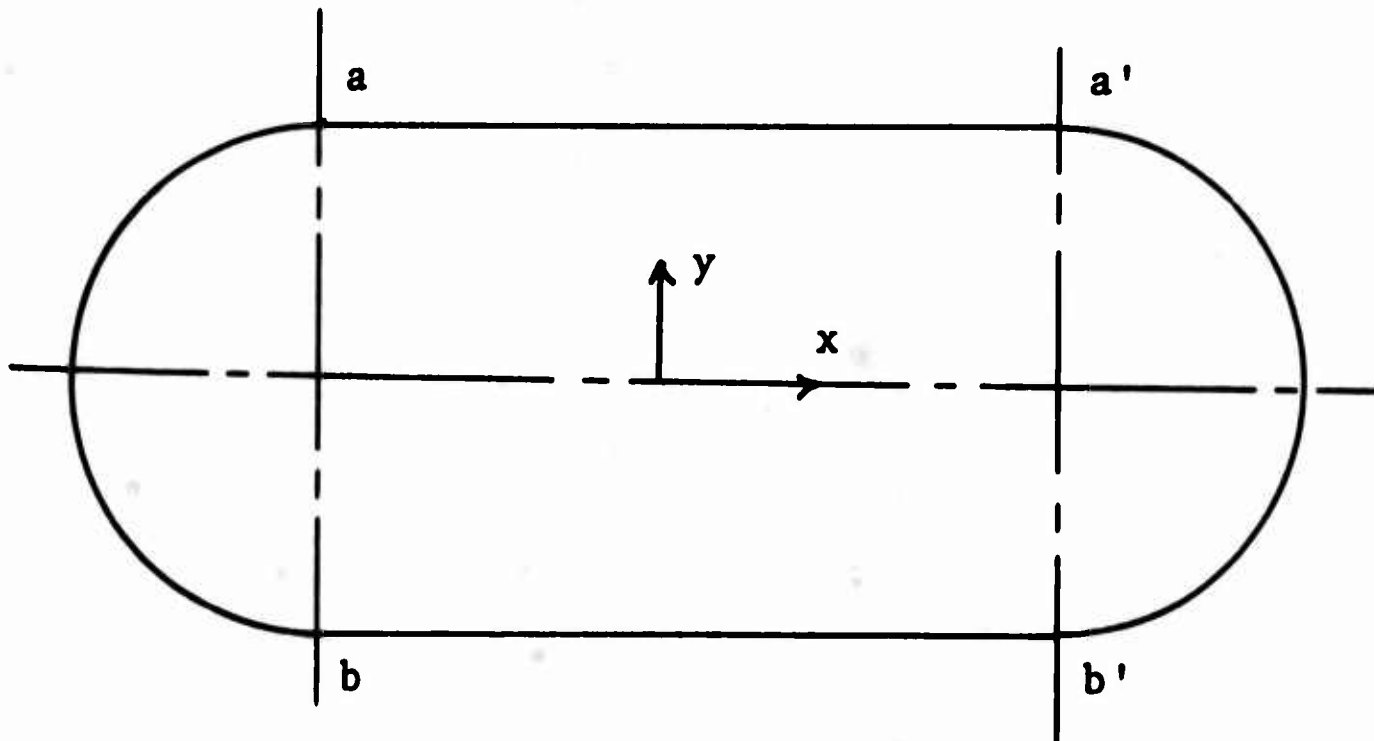
p = Internal pressure (lb/in²)

r = Radius (in)

t = Thickness (in)

Timoshenko and Woinowsky-Krieger (Ref 20;482) show that the extension of the radius of the cylindrical shell under an internal pressure is

$$\delta_c = \frac{pr^2}{Et} (1 - \nu/2)$$



Length of Cylinder = 40 ft

Total Length = 65 ft

Diameter = 25 ft

Surface Area = 5100 ft²

Volume = 27,820 ft³

Fig. 4

Overall Geometry of Space Hangar

and that the extension of the radius of the hemispherical ends is

$$\delta_h = \frac{pr^2}{2Et} (1 - \nu) \quad (17)$$

where

δ_c = Change in radius of the cylinder (in)

δ_h = Change of radius of hemispherical ends (in)

p = Internal pressure (lb/in²)

r = Radius (in)

t = Thickness of wall (in)

E = Youngs Modulus (lb/in²)

ν = Poissons Ratio

It may be concluded from equations (16) and (17) that if only the stresses found from membrane theory are used, a discontinuity at the joints ab and a'b' is obtained. Therefore, there must act at the joints shearing forces (Q) and bending moments (M) which are uniformly distributed along the circumference (Fig. 5). Timoshenko and Woinowsky-Krieger (Ref 20:483) suggest that an approximate solution of the problem can be determined by assuming that the bending is of importance only in the zone of the hemispherical shell close to the joint and that this zone can be treated as a portion of the cylindrical shell of radius r. Timoshenko and Woinowsky-Krieger further state that if the thicknesses of the cylinder and the hemispherical ends are

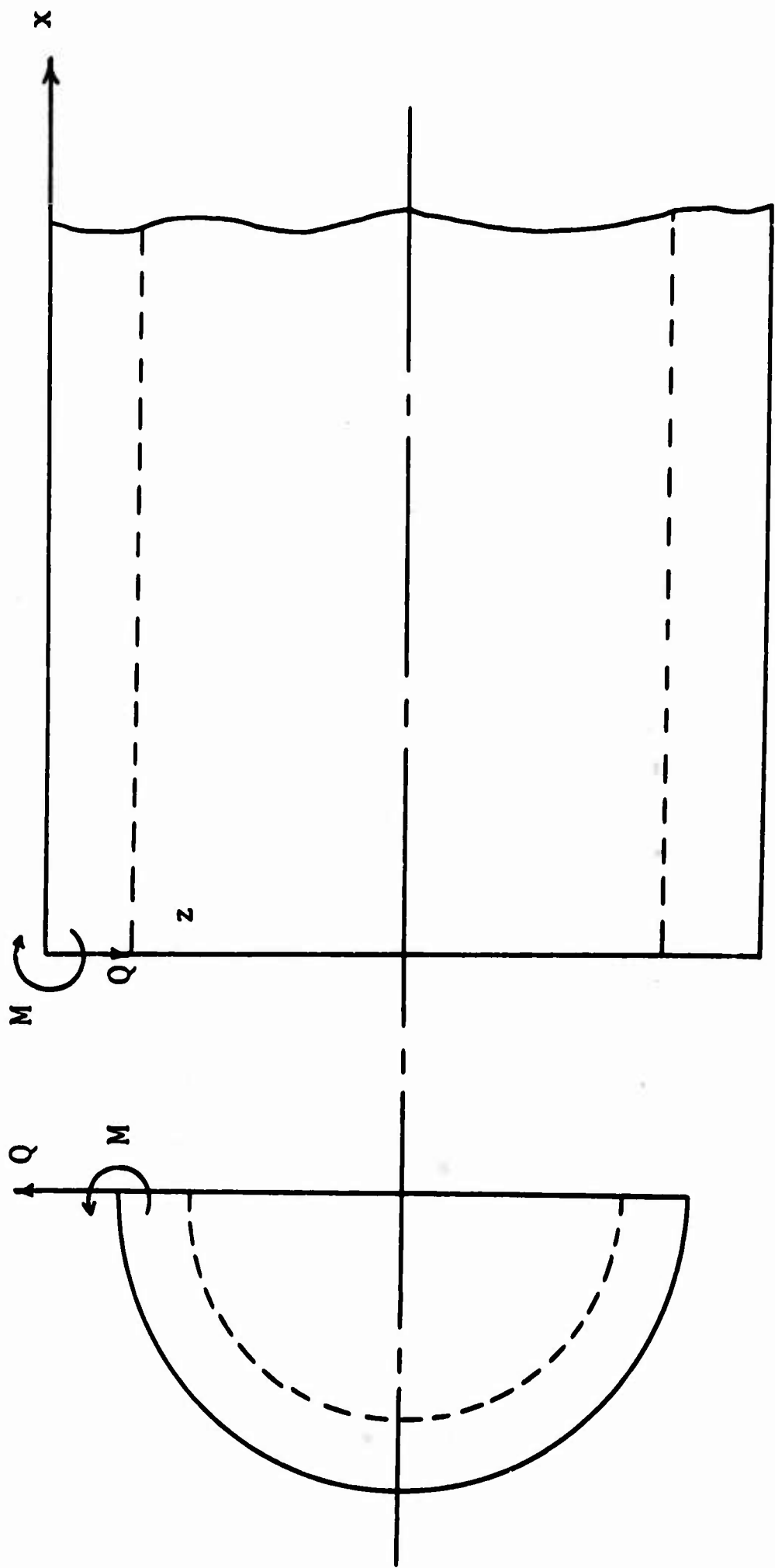


Fig. 5

Moments and Forces at the Joints

the same, the forces (Q) produce equal rotations of the edges of both portions at the joint. This indicates that the moment (M) vanishes and the force (Q) alone is sufficient to eliminate the discontinuity.

The problem of a cylindrical vessel with hemispherical ends is presented in Timoshenko and Woinowsky-Krieger (Ref 20:482-484). The derivation of the maximum stress is not presented in this paper but is shown in Ref 20. The result of this analysis is that the maximum stress for determining the thickness in the design of a vessel when $\gamma = 0.3$ is

$$\sigma_{\max} = 1.032 pr/t \quad (18)$$

where

σ_{\max} = Maximum stress (lb/in²)

r = Radius (in)

p = Pressure (lb/in²)

t = Thickness (in)

Thickness Determination

Using equation (18)

$$\sigma_{\max} = 1.032 pr/t \quad (18)$$

with the following values

$$\sigma_{\max} = 26,000 \text{ lb/in}^2$$

$$r = 150 \text{ in}$$

$p = 15 \text{ lb/in}^2$ (Safety factor of 2.0 is applied to design internal pressure of 7.5 lb/in^2)

the thickness of the load-carrying member is 0.0895 in. Using equation (14), the thickness required would be 0.0867. Because the difference of these two thicknesses is extremely small and because of the relative difficulty in fabricating a variable thickness layer of fiberglass wall, it is concluded that the pressure vessel layer of the composite wall be constructed with a uniform thickness of 0.0895 in.

VII. Pressure Maintenance

The loss of environmental gases from a space vehicle presents a very serious design problem. The more complex the vehicle design the greater the number of possible leakage sources that must be considered. Based on any design parameters, leakage can be expected to arise from the following sources: (1) leakage through bonded, welded, and mechanical joints, (2) leakage through seals and hatches, and (3) leakage through permeable skins, coatings, and sealing materials. The first two leakage sources are primarily a design problem and the third leakage source is a material problem.

The loss of environmental gases through the permeable skin is the subject of this section. The leakage rate caused by diffusion through the vehicle wall varies approximately directly with the pressure differential across the wall. Younger et al. (Ref 21:70) suggest that the leakage rate for a given pressure can be determined by the following equation

$$L = \frac{PA}{t} \quad (12)$$

where

L = Leakage rate (ft³/day)

P = Permeability of the material (ft³-mil/ft²-day)

A = Surface area of the structure (ft²)

t = Thickness of the material (mil)

The permeabilities of some film materials, based on a pressure differential of 7.5 psi, are presented in Table IX. The leakage rates, computed from equation (12), are presented in Table X. Polyvinylidene chloride appears to be the best material to use as a gas barrier because it not only possesses the desired material property of low gas permeability but also the desired material properties of flexibility and toughness.

It is possible that the gases of the artificial environment, after they have permeated the gas barrier of polyvinylidene chloride, may become trapped in the interior of the composite wall. The pressures exerted by these gases could cause enough internal forces to separate the laminated materials from each other and, thereby, cause a compromise in the desired and necessary protection afforded by the wall. Because of the high permeability of polyurethane foam, a layer of polyurethane foam is used in conjunction with the gas barrier of polyvinylidene chloride and is vented to the vacuum of space. These vents then permit escaping gases to pass directly into space and, thereby, reduce the possibility of causing the laminated materials to separate. The polyurethane foam also serves in helping to erect the structure in space through its elastic recovery.

Table IX

Permeability of Some Materials

NOTE: Permeability based on internal pressure of 7.5 psi with a partial pressure of oxygen of 3.5 psi and a partial pressure of nitrogen of 4.0 psi

Material	Permeability to Gases x 10 ⁺⁵ (ft ³ -mil/ft ² -day)			
	Nitrogen	Oxygen	Carbon Dioxide	Water Vapor @ 100% Humidity
Polyvinylidene Chloride	1.19	3.64	21.8	27.8
Polyester Terephthalate	1.66	6.79	65.4	3595.0
Polyvinyl Chloride	60.50	149.00	140.4	--
Polytetrafluoroethylene	13.25	36.00	--	--
Polyimide	8.03	29.00	--	--

(From Ref 2:28)

Table X

Leakage Rates of Some Materials

NOTE: Leakage rate based on a surface area of 5100 ft² and a thickness of 1 mil

Material	Leakage Rate (ft ³ /day)			
	Nitrogen	Oxygen	Carbon Dioxide	Water Vapor @100% Humidity
Polyvinylidene Chloride	0.061	0.186	1.11	1.42
Polyester Terephthalate	0.085	0.346	3.32	1832.00
Polyvinyl Chloride	3.085	7.600	7.14	----
Polytetrafluoroethylene	0.676	1.840	----	----
Polyimide film	0.410	1.510	----	----

VIII. Proposed Design of Composite Wall

As a result of the preceding sections, it is possible to propose a design for a composite wall. There are many different combinations of materials and many different methods of arranging the materials in a design of a composite wall for an expandable space hangar. One possible design based on a probability of no meteoroid penetration of 99.9% is presented here.

The outer facing, whose primary function is thermal and radiation control, is aluminized polyester terephthalate. It is proposed that the polyester terephthalate be 5 mils thick and have a coating of vapor deposited aluminum with a thickness of 0.2 mils. This thin layer of vapor deposited aluminum not only keeps the internal temperature of the composite wall at a tolerable level but also serves as an ultraviolet radiation reflector.

The primary purpose of the second layer is to fragment impinging meteoroids. 181 style glass cloth is used in this capacity because of its excellent ability to fragment meteoroids. This is a laminated layer of fiberglass composed of 21 sheets, each of which is 9 mils thick. Therefore, the total thickness of this layer is 0.189 inches.

The next or third layer is 1 inch of polyurethane foam. This foam core has two very important functions. Initially, the potential energy stored in the foam is used to deploy and erect the structure in space. The second function of the polyurethane foam is the absorption of the fast moving particles of the fragmented meteoroid. Although only 0.409 inches of foam is needed to absorb the fast moving particles of the fragmented meteoroid, one inch of foam is used in order to aid in the erection of the structure in space.

The fourth layer of the composite wall is 0.252 inches of polyester terephthalate. This layer is a laminate with 18 sheets of 14-mils thickness. It has two very important functions. First, the polyester terephthalate serves as a radiation shield for the occupants of the structure and second, it serves as an absorber of the slower moving particles of a fragmented meteoroid.

The fifth layer, like the third layer, is 1 inch of polyurethane foam. Its purpose is also to erect the structure in space by means of the elastic recovery concept. This foam is vented to the vacuum of space in order to permit escaping gases of the artificial atmosphere of the hangar to dissipate in the vacuum of space; thereby, reducing the possibility of having gases trapped between layers of the composite wall.

The sixth layer is the pressure vessel member of the composite wall. It is a laminate of rigidized 181 style glass cloth (urethane resin moisture cured) with a total thickness of 0.09 inches. It contains 10 sheets of 9-mils thickness.

The seventh layer of the composite wall is the gas barrier with the function of keeping the artificial atmosphere in the hangar. The material used is polyvinylidene chloride with a thickness of 1 mil.

The proposed composite wall is approximately 2.54 inches thick and weighs approximately 5.78 lb/ft^2 . The total surface area is 5100 ft^2 and the total weight of the composite wall is approximately 29,500 lbs. Table XI shows the thickness, weight per square foot, and purpose of each layer of the composite wall. Figure 6 shows a cross-section of the proposed composite wall.

Table XI

Thickness, Weight, and Purpose of Components
of Proposed Composite Wall

Layer	Material	Thickness (in)	Weight (lb/ft ²)	Purpose
1	Polyester Terephthalate (Aluminized)	0.0052	0.0283	Thermal and radiation control
2	181 Style Glass Cloth	0.1890	2.4950	Fragment impinging meteoroids
3	Polyurethane Foam	1.0000	0.1670	Elastic recovery and absorber of fast moving particles of fragmented meteoroid
4	Polyester Terephthalate	0.2520	1.7300	Radiation shield and absorber of slow moving particles of fragmented meteoroid
5	Polyurethane Foam	1.0000	0.1670	Elastic recovery
6	181 Style Glass Cloth	0.0900	1.1830	Pressure vessel
7	Polyvinylidene Chloride	0.0010	0.0132	Gas barrier

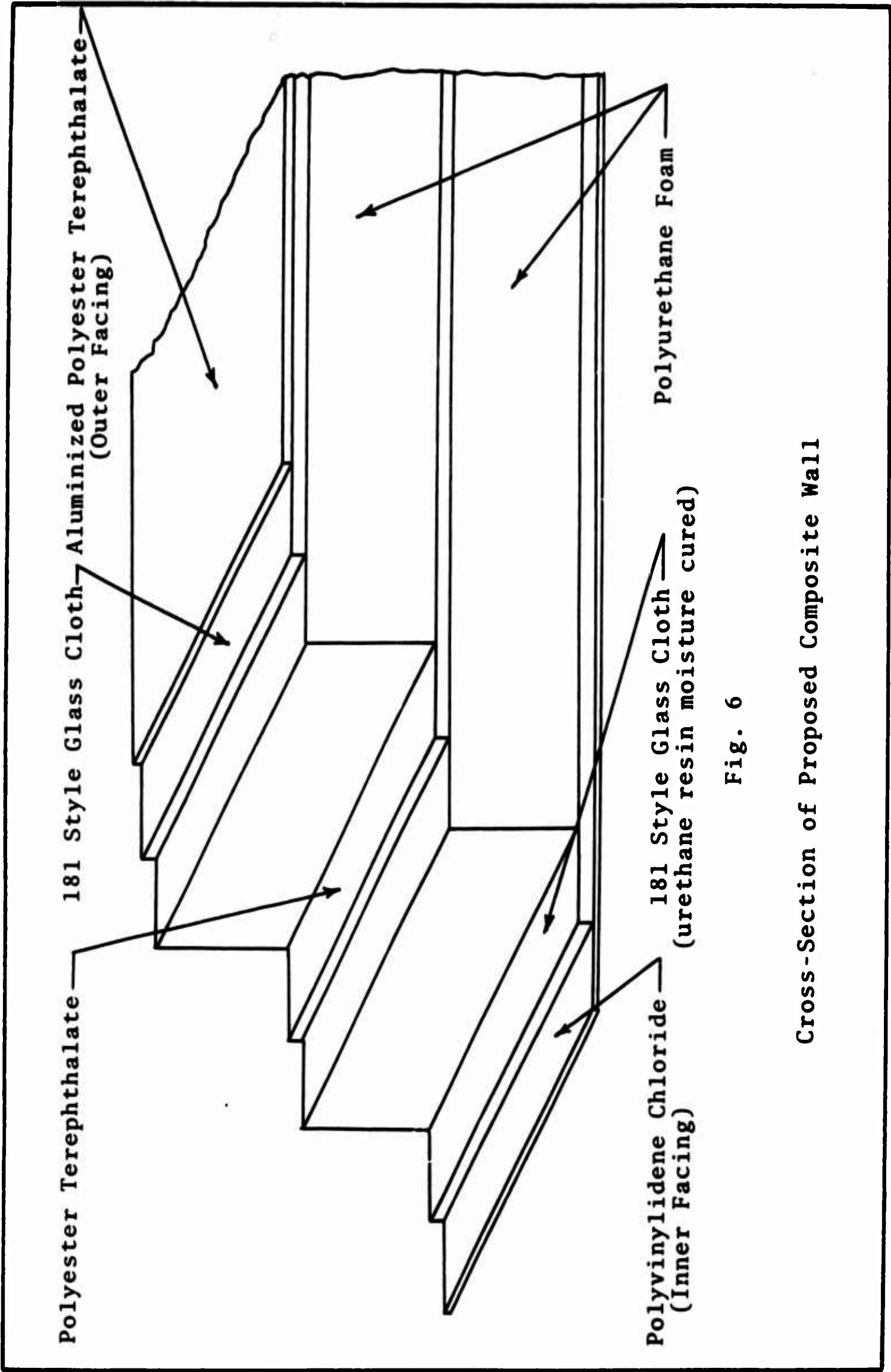


Fig. 6

Cross-Section of Proposed Composite Wall

IX. Packaging, Erecting, and Rigidizing
the Composite Wall

Packaging

From a review of the literature, it appears that the packaging of an expandable structure involves basically a trial-and-error method. However, there are a few general rules which can be employed in the folding of an expandable structure. Since the mechanism for erection comes from elastic recovery, the folding procedures affect the speed of unfurling. In general, it is better to have many minor folds rather than a few major folds. A major fold is defined as a fold along an axis of symmetry whereas a minor fold is any fold which is not major. Because the folding imparts potential energy to the structure and reduces its volume, the folding procedure is important. The more folding that is accomplished, the greater the potential energy is available for a faster deployment of the structure.

From experimental studies done by Brink, et al. (Ref 2:67), the ratio of the expanded volume to a possible package volume was determined. The results of this study are shown in Fig. 7. Brink, et al. (Ref 2:66) suggest that the effective thickness of the composite wall can be determined by allowing the foam core to reduce to one-

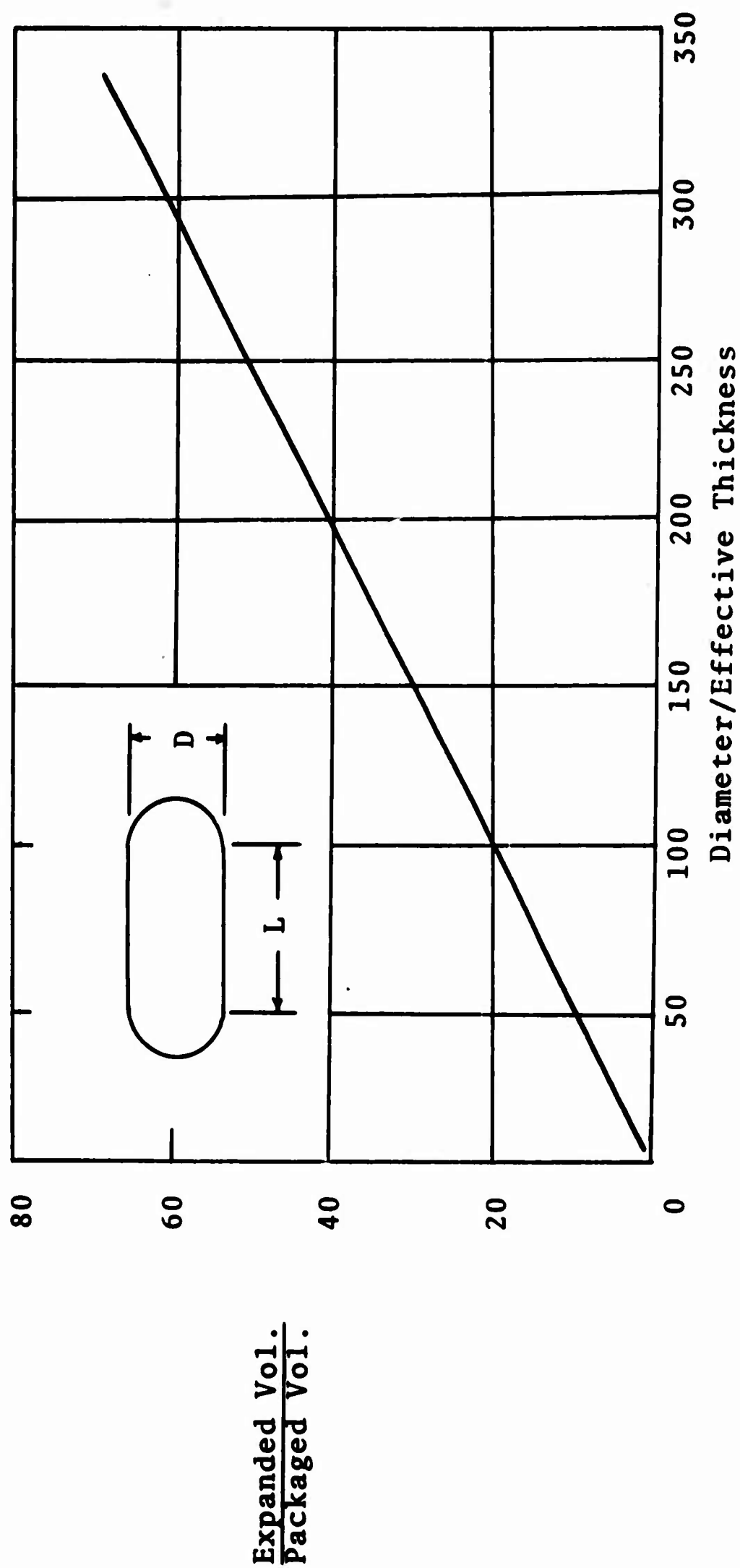


Fig. 7

Volume Ratio vs. Diameter to Effective Thickness Ratio

(Ref 2:67)

fourth its original thickness. The other materials, being more or less incompressible, have their effective thickness equal to their original thickness. The effective thickness of the composite wall proposed in this study is 1.037 inches. With a diameter (D) of 25 feet and a length (L) of 40 feet, the L/D ratio is 1.6 and the ratio of the diameter to the effective thickness is 290. From Fig. 7, with a diameter to effective thickness ratio of 290, the ratio of the expanded volume to the packaged volume is approximately 61. Therefore, with an expanded volume of $27,820 \text{ ft}^3$, the packaged volume is approximately 460 ft^3 . Since a cylindrical shaped canister would probably offer a better package container than a spherical shaped canister because it would be geometrically similar to the expanded structure, a cylindrical canister with an approximate length of 10 feet and diameter of 7.7 feet is proposed.

Erecting

One of the primary disadvantages of an expandable space structure is the probability of the structure failing to deploy. This study proposes two methods of deployment. It is felt that the elastic recovery principle would suffice as a means of deploying the structure. From experiments performed by Brink, et al. (Ref 2:37) on a cylinder with a length of 10 inches and with a diameter of 10 inches, and with a ratio of expanded volume to packaged

volume of 22, it took the cylinder approximately 10 minutes to expand immediately after it had been packaged and it took the cylinder approximately 2 hours to expand after it had been packaged for 6 weeks. It was concluded therefore that the elastic recovery concept will perform its primary function of causing the structure to regain its original shape. Along with the expansion based on the elastic recovery concept, it is proposed that during the erection phase, air pressure be released inside the hangar to aid in its deployment.

Rigidizing

The curing agent for rigidizing the hangar is moisture. Tests performed by Rochon, et al. (Ref 16:110) show that a moisture cure is possible. The air released inside the hangar to aid in its deployment would be of high moisture content and this moisture would be the curing agent for the pressure vessel of 181 style glass cloth (urethane resin moisture cured).

X. Conclusions

Selection of Materials

Investigators have determined generally what materials will show the least degradation when exposed to various environments simulating the radiation, vacuum, or temperature of space. Of course, the interaction of temperature, radiation, and vacuum will in all probability tend to accelerate the degradation processes. Until more comprehensive experimental studies are made and on the basis of experience with such satellites as those of the Echo series, it can only be assumed that the space environment will have negligible detrimental effects on the engineering properties of the selected materials over the one year time period considered in this study. It can generally be anticipated that the proposed materials when placed in a composite wall will not degrade as rapidly as they would if they were exposed to the space environment individually.

Based on a review of available data, it was decided that the following materials can be expected to perform satisfactorily in an expandable space maintenance hangar:

- (1) Polyester terephthalate
- (2) Polyurethane foam
- (3) 181 style glass cloth reinforced polyester

(4) 181 style glass cloth (urethane resin moisture cured)

(5) Polyvinylidene chloride

Meteoroid Shielding

As the probability of a meteoroid penetrating a structure decreases, the size of the critical meteoroid with which the designer has to contend increases. Therefore, the thickness and weight of the composite wall needed to stop the larger meteoroid increases. For a probability of no penetrations of 99.0%, the thickness and weight of the composite wall are 0.455 inches and 2.235 lb/ft^2 respectively. If the designer desires a probability of 99.5%, the thickness of the composite wall increases by only 0.081 inches and the weight increases by only 0.416 lb/ft^2 . However, if the designer desires to increase the probability from 99.5% to 99.9%, the thickness of the wall increases by 0.286 inches and the weight of the wall increases by 1.395 lb/ft^2 . Almost all design problems are characterized by compromises. However, this writer concludes that the additional weight associated with the probability of 99.9% is warranted and therefore concludes that the composite wall design associated with a probability of no penetrations of 99.9% be used.

Based on a probability of no penetrations of 99.9%, a composite wall using 181 style glass cloth, polyurethane

foam, and polyester terephthalate is designed. At least 0.183 inches of 181 style glass cloth is needed to fragment the incoming meteoroid, at least 0.409 inches of polyurethane foam is needed to absorb the fast meteoroid particles, and at least 0.230 inches of polyester terephthalate is needed to stop the slow meteoroid particles. This gives a total thickness of 0.822 inches and assures that a probability of no meteoroid penetration of 99.9% exists.

Radiation Shielding

Even though the energies of electrons are much lower than the energies of protons, the enormous flux of the electrons make them the primary radiation hazard for a circular orbit of 500 kilometers. Because approximately 88% of the incident energy of the electron spectrum is associated with the electrons with energies equal to or less than 2 Mev, it was felt that the shielding should be devised for the 2 Mev electron. This requires 0.255 inches of polyester terephthalate and would expose the astronauts to a total radiation dose of not more than 0.1661 rads/day. With an average dose of 0.1661 rads/day, an astronaut could spend well over a year in the space hangar and still remain below the assumed allowable accumulative dose of 200 rads. However, it must be remembered that the astronauts will be leaving and entering the hangar as they perform their primary tasks of space maintenance. Furthermore,

other items such as reliability of performance and human factors will be the limiting criterion in the amount of time an astronaut is able to spend assigned to the maintenance hangar.

Pressure Maintenance

Polyvinylidene chloride appears to be the best material to use as a gas barrier because it not only possesses the desired low permeability but also flexibility and toughness. A foam layer, vented to space, is used in conjunction with the gas barrier to permit escaping gases of the artificial environmental atmosphere of the hangar to dissipate into space thereby reducing the probability of having gases trapped between layers of the composite wall. The amount of environmental gases lost through the walls is negligible.

Pressure Vessel

Using the membrane analysis and an approximate solution for the discontinuities at the joints, the required minimum thickness of the fiberglass cloth which carries the pressurization loads is found to be 0.0895 inches. Because of the relative difficulty in fabricating a variable-thickness layer, it is concluded that the fiberglass should be of uniform thickness.

Proposed Design of Composite Wall

The proposed composite wall has seven layers, has a thickness of 2.54 inches, and has a total weight excluding adhesives of approximately 29,500 pounds. The thickness and weight per unit area are presented in Table XI on page 71. The proposed wall affords the occupants protection from radiation and meteoroids, has a low gas permeability, and withstands an internal pressure of 7.5 lb/in².

Packaging, Erecting, and Rigidizing the Composite Wall

It is concluded that the wall of a hangar with an expanded volume of 27,820 ft³ can be packaged in an approximate volume of 460 ft³. The package canister is cylindrical with a length of approximately 10 feet and with a diameter of approximately 7.7 feet. It is also concluded that the elastic recovery concept will perform its primary function of causing the structure to regain its original shape. However, because moisture is needed to rigidize the 181 style glass cloth, air with a high humidity will be released inside the structure and will aid in the erection of the structure.

Summary

The purpose of this study was to investigate the feasibility of designing an expandable space maintenance hangar using the elastic recovery concept. In order to be considered feasible, this study, required that a wall be

designed which would afford astronauts protection from the space environment, that this wall be constructed from materials which would enable it to be packaged into a small volume for launch, and that the structure automatically deploy and cure in space. It was assumed that if the wall could be built, the other problems associated with the design could be solved. Based on the results of this study, the writer concludes that it is feasible to design an expandable structure which could be employed as a maintenance hangar for space use.

XI. Recommendations for Further Study

The following items suggest areas for further study which could not be investigated in detail or had to be assumed in this feasibility study:

1. An investigation is necessary into the construction processes to determine how the proposed composite wall could be fabricated.
2. An experimental investigation is necessary to determine the actual effects of the space environment on the proposed wall. This investigation should simulate as closely as possible the space environment. In other words, the interaction of temperature, radiation, and vacuum should be investigated.
3. The analysis of the meteoroid penetration of the composite wall must be further refined. Experimental verification of the theory is also necessary.
4. The radiation analysis needs further refinement. An experimental investigation on the actual radiation protection afforded by the proposed composite wall is necessary.
5. Folding procedures and patterns need to be developed in order to optimize the ease and speed of deployment.
6. An analytical and experimental thermal analysis

for the proposed design is necessary.

7. A design of an internal structure to carry maintenance loads and support maintenance equipment is necessary.

8. A design of a door and hatches for the hangar is necessary.

9. An analysis is necessary to evaluate the loadings which the hangar might experience during orbital and rendezvous maneuvers.

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Appendix A

Sample Calculations for Determining
Critical Meteoroid Properties

This appendix gives some sample calculations using the formulas presented, discussed, and referenced in Chapter IV. For ease of reference, the equation numbers used in this appendix refer to those of Chapter IV. These sample calculations are for determining the critical meteoroid properties based on a probability of no penetration of 99.9%. A critical meteoroid is defined as the largest meteoroid which must be stopped by a wall in order to assure a given probability of no penetrations.

The first step in the determination of the critical meteoroid properties is the calculation of the planetary shielding factor, s . The planetary shielding factor is defined by equation (3).

$$s = (1 + \cos \theta) / 2 \quad (3)$$

where

$$\sin \theta = R / (R + H)$$

R = Radius of shielding body (earth)

H = Altitude above shielding body

Assuming that for a low earth orbit $\sin \theta = 1$, the planetary shielding factor is found to be equal to 1/2.

The meteoroid flux is now determined using equation (2).

$$\text{Log } P(0) = -0.434 N A T s \quad (2)$$

where

$P(0)$ = Probability of no penetrations (0.999)

N = Meteoroid flux (particles/ft² - day)

A = Surface area of the structure (ft²)

T = Time in orbit (days)

s = Planetary shielding factor

$$\text{Log } 0.999 = 0.434 N (5100)(365)(0.5)$$

$$N = 9.9 \times 10^{-10} \text{ particles/ft}^2 \text{ - day}$$

The mass m_m of the critical meteoroid is now determined using equation (1).

$$\text{Log } N = -1.34 \text{ Log } m_m - 10.423 \quad (1)$$

$$\text{Log } m_m = \frac{10.423 - 0.9956 - 10}{-1.34}$$

$$= -1.06$$

$$m_m = 8.71 \times 10^{-2} \text{ gms}$$

$$= 19.3 \times 10^{-5} \text{ lbs}$$

The volume of the critical meteoroid \bar{V}_m is determined by dividing the mass by the density.

$$\bar{V}_m = m_m / \rho_m \quad (19)$$

$$= (193/7.25 \times 10^{-4})$$

$$= 2.66 \times 10^{-3} \text{ in}^3$$

Assuming the critical meteoroid is spherical, the diameter, D_m , is determined from the relationship

$$D_m = (6 \bar{V}_m / \pi)^{1/3} \quad (20)$$

$$\begin{aligned} D_m &= (6 \times 0.00266 \times 1/\pi)^{1/3} \\ &= 0.172 \text{ in} \end{aligned}$$

Table II on page 26 shows the critical meteoroid properties for the probability of no penetrations of 99.0%, 99.5%, and 99.9%. From this table, it is evident that as the probability of puncture decreases the critical mass, volume, and diameter of the meteoroid increase.

Appendix B

Sample Calculations for Determining
Thickness of Composite Wall

This appendix gives some sample calculations using the formulas presented, discussed, and referenced in Chapter IV. For ease of reference, the equation numbers used in this appendix refer to those of Chapter IV. These sample calculations are for determining the thickness of a composite wall necessary for protection from a critical meteoroid based on a probability of no penetration of 99.9%.

The composite wall design for meteoroid protection is composed of three layers. The outer facing is constructed of 181 style glass cloth and serves as a meteoroid bumper with the function of fragmenting the incoming meteoroid. After the meteoroid is fragmented, the resulting particles are divided into two groups, the faster group and the slower group. The second layer is a foam core constructed of polyurethane foam with the function of absorbing particles of the faster group. The third layer, polyester terephthalate, has the function of stopping particles of the slower group.

In the penetration equations, (4) through (7), the subscript t refers to the target material. In this appendix, the subscript 1 refers to the target material 181 style glass cloth, the subscript c refers to the target material polyurethane foam, and the subscript 2 refers to the target material polyester terephthalate.

Outer Facing Thickness

The function of the outer facing of 181 style glass cloth is fragmentation of the incoming meteoroid. In computing the thickness t_1 necessary to fragment an incoming meteoroid, the following material properties are taken from Table XII;

$$\begin{aligned}S_1 &= 1420 \text{ lb/in}^2 \\ \rho_1 &= 0.0916 \text{ lb/in}^3 \\ Z_1 &= 0.180\end{aligned}$$

From Figure 8

$$t_1/t'_p = 0.10$$

Using the penetration formula for a velocity range from 70,000 to 240,000 ft/sec, equation (7), because the incoming meteoroid is assumed to be traveling at a velocity of 100,000 ft/sec, the thickness of the outer facing material t_1 is found.

Table XII
Properties of Proposed Materials Necessary for
Meteoroid Penetration Analysis

Material	Property		
	Shear Yield Stress, (S) (lb/in ²)	Density ₃ (ρ) (lb/in ³)	Bumper Parameter ^a , (Z)
181 Style Glass Cloth	1420 ^b	0.0916 ^c	0.180
Polyurethane Foam	40 ^d	0.00116 ^c	N.A.
Polyester Terephthalate	940 ^e	0.0476 ^f	0.0617

^a Bumper Parameter (Z) $S_1 \rho_1 / S_m \rho_m$

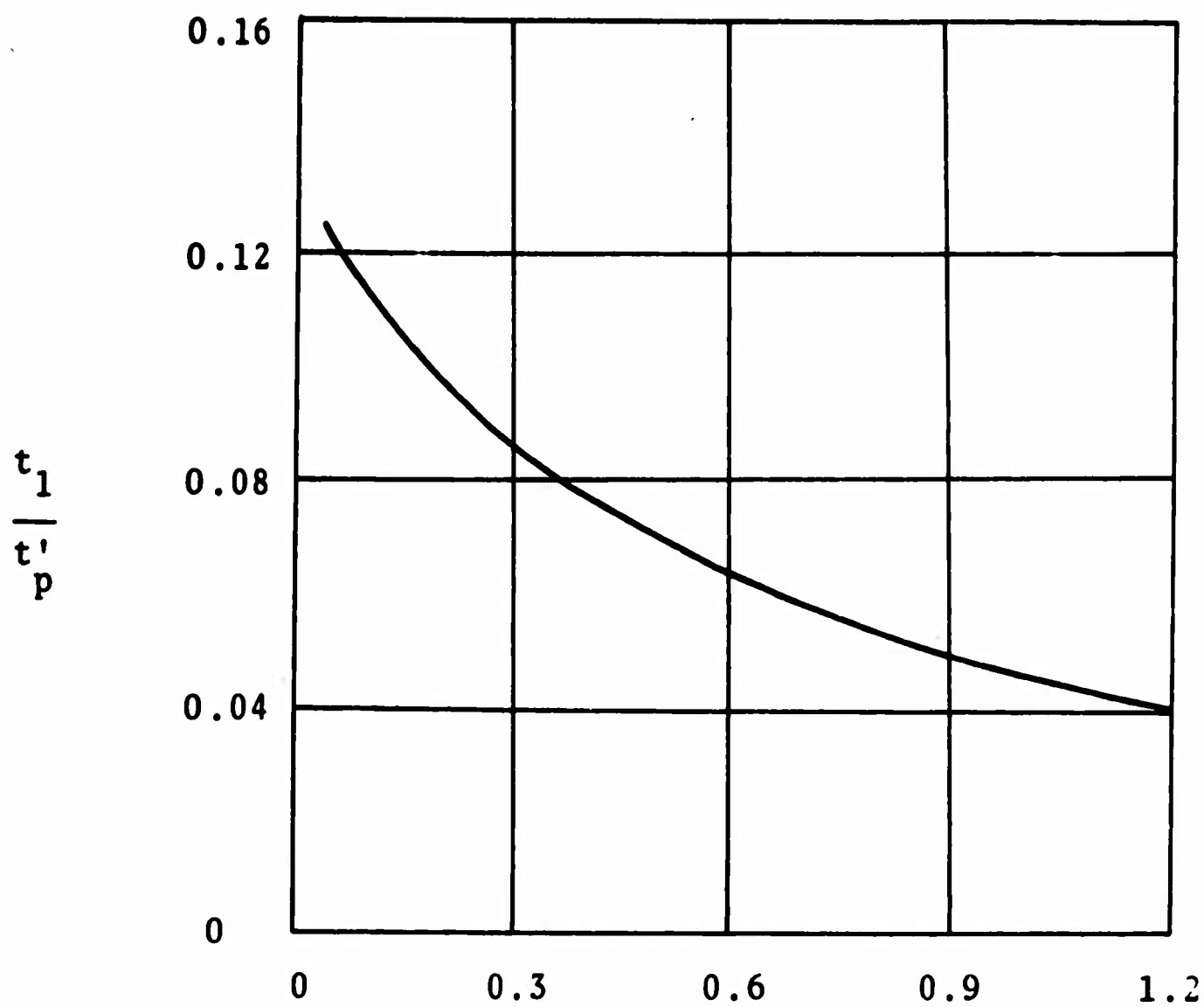
^b Ref 13:2-6

^c Letter from N.S. Hanssen of the GCA Viron Division (see Appendix D)

^d Ref 1:66

^e Letter from N.O. Brink of the Whittaker Corporation (see Appendix D)

^f Ref 2:65



$$z_1 = \frac{S_1 \rho_1}{S_m \rho_m}$$

Fig. 8

t_1/t'_p VS. z_1

(Ref 2:186)

$$t'_p = 1.5(0.97) V^{0.18} \rho_m^{0.26} S_1^{-0.04} \rho_1^{-0.46} \bar{V}_m^{0.33} \quad (7)$$

$$t_1 = 0.10(1.5)(0.97)(100,000)^{0.18}(0.0725)^{0.26} \times \\ (1420)^{-0.04} (0.0916)^{-0.46} (0.00266)^{0.33} \\ = 0.183 \text{ in}$$

Therefore, the thickness of the outer layer of 181 style glass cloth must be at least 0.183 inches if the probability of no penetrations is to be 99.9%. If the thickness is less than 0.183 inches, a critical meteoroid would not be fragmented enough for absorption by the second and third layers and would cause a penetration of the structure.

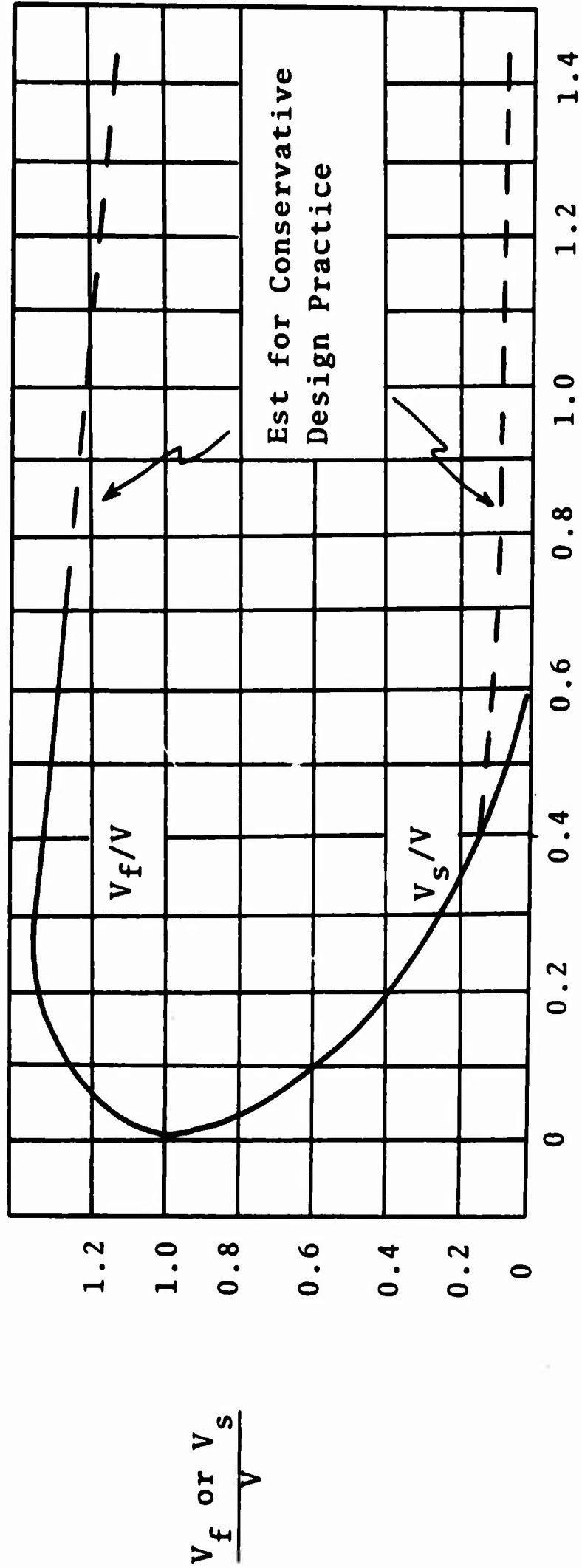
Core Thickness

The second layer is a core of polyurethane foam which functions as an absorber of the fast moving particles of the fragmented meteoroid. In order to calculate the thickness of foam required, the velocities of the fast fragments V_f and of the slow fragments V_s must be determined. For outer facing:

$$\frac{\text{wt. of shield/unit area}}{\text{wt. of meteoroid/unit area}} = \frac{(0.0916)(0.183)}{(0.0725)(0.172)} \\ = 1.34$$

From Figure 9

$$V_f = 1.15(100,000) = 115,000 \text{ ft/sec} \\ V_s = 0.10(100,000) = 10,000 \text{ ft/sec}$$



$$\frac{\text{Wt. of Shield/Unit Area}}{\text{Wt. of Projectile/Unit Area}}$$

Fig. 9

Velocity Ratio vs. Shield/Projectile Weight

(Ref 2:188)

The equivalent density of fragments is found from the average density of the outer facing material and the impacting meteoroid.

$$\begin{aligned}\rho_a &= \frac{\rho_l + \rho_m}{2} \\ &= (0.0916 + 0.0725)/2 \\ &= 0.0821 \text{ lb/in}^3\end{aligned}$$

The material properties of polyurethane foam are taken from Table XII .

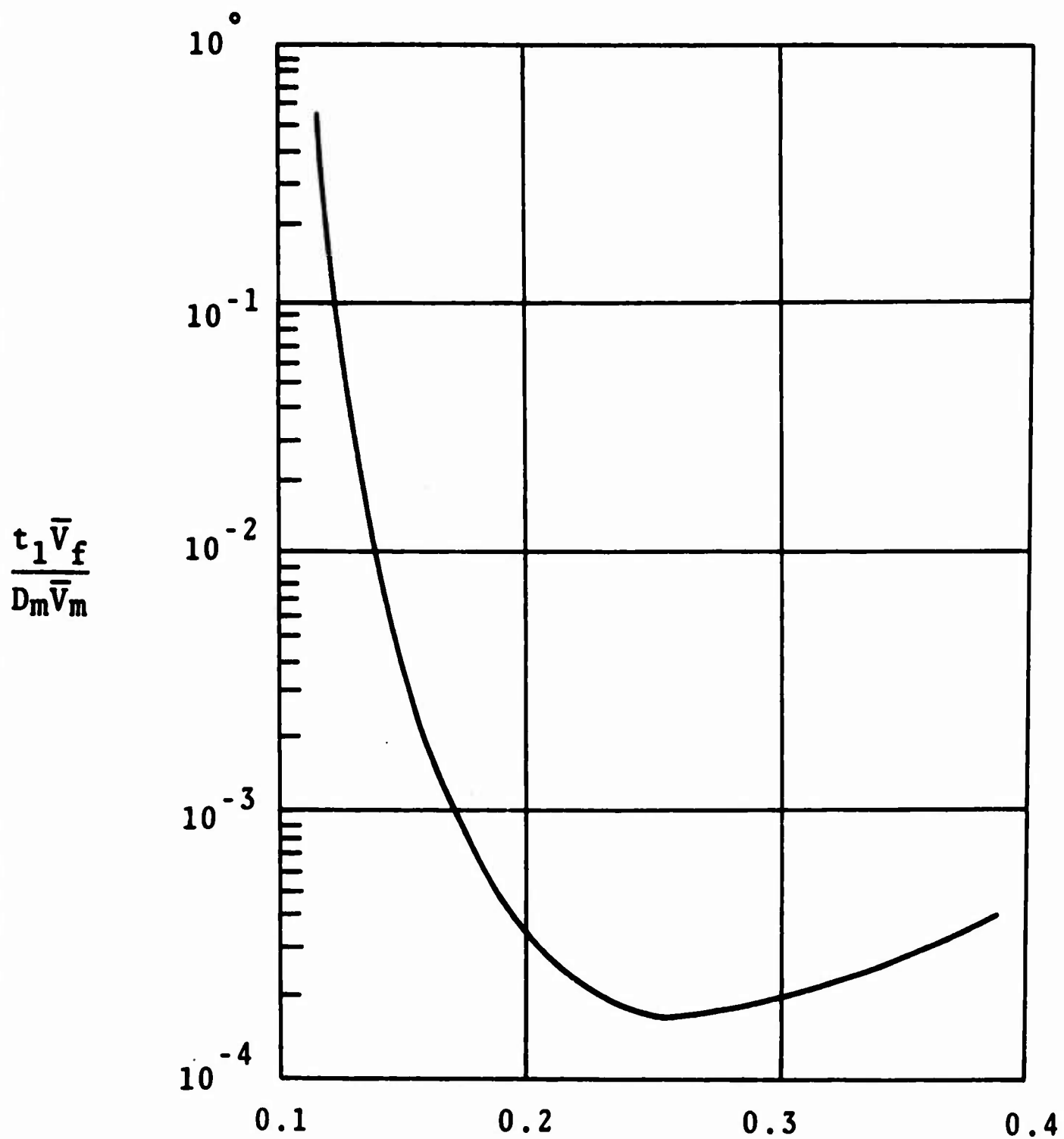
$$\begin{aligned}S_c &= 40 \text{ lb/in}^2 \\ \rho_c &= 0.00116 \text{ lb/in}^3\end{aligned}$$

From Figure 10 with the bumper parameter Z_1 equal to 0.180, a reference volume \bar{V}_r is determined based on a reference velocity of 20,000 ft/sec.

$$\begin{aligned}t_1 \bar{V}_r / D_m \bar{V}_m &= 4 \times 10^{-4} \\ \bar{V}_r &= (4 \times 10^{-4}) (0.172) (26.6 \times 10^{-4}) / 0.183 \\ &= 10^{-6} \text{ in}^3 \text{ for } V_r = 20,000 \text{ ft/sec}\end{aligned}$$

To find the volume of the fast particles ($V_f = 115,000$ ft/sec), the following equation is used (Ref 2:192):

$$\begin{aligned}V_f &= \bar{V}_r V_f^{0.18} V_r^{-0.449} \quad (22) \\ &= (10^{-6}) (115,000)^{0.18} (20,000)^{-0.447} \\ &= 98 \times 10^{-9} \text{ in}^3\end{aligned}$$



$$Z_1 = \frac{S_1 \rho_1}{S_m \rho_m}$$

Fig. 10

Estimated Variation of \bar{V}_f vs. Bumper Parameter Z_1

(Ref 2:191)

Using equation (7), the core thickness is determined.

$$\begin{aligned}
 t_c &= 1.5(0.97) V_f^{0.18} \rho_a^{0.26} S_c^{-0.04} \rho_c^{-0.46} V_f^{0.33} \quad (7) \\
 &= 1.5(0.97)(115,000)^{0.18} (0.0821)^{0.26} (40)^{-0.04} \times \\
 &\quad (0.00116)^{-0.46} (98 \times 10^{-9})^{0.33} \\
 &= 0.409 \text{ in}
 \end{aligned}$$

Therefore at least 0.409 inches of polyurethane foam is needed to absorb the faster meteoroid fragments.

Inner Facing Thickness

The thickness of the third layer, polyester terephthalate, with the condition that it must absorb the slow meteoroid particles, is now computed.

From Figure 11 with a bumper parameter equal to 0.180, the volume of the slower fragments is determined.

$$t_1 \bar{V}_s / D_m \bar{V}_f = 5.4$$

$$\begin{aligned}
 \bar{V}_s &= 5.4(0.172)(98 \times 10^{-9})/0.183 \\
 &= 497 \times 10^{-9} \text{ in}^3
 \end{aligned}$$

The material properties of polyester terephthalate are taken from Table XII.

$$S_2 = 940 \text{ lb/in}^2$$

$$\rho_2 = 0.0476 \text{ lb/in}^3$$

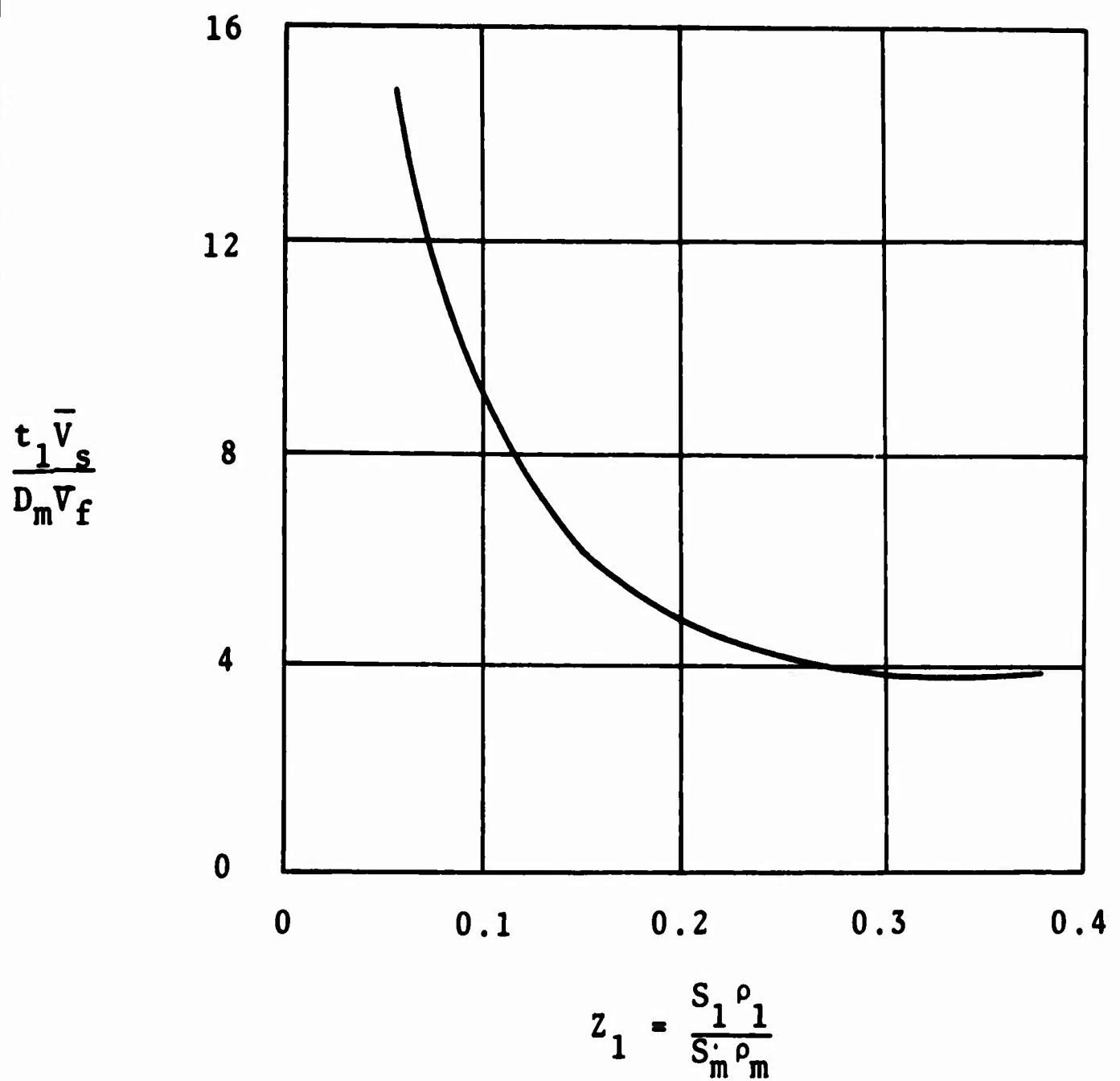


Fig. 11

Variation of \bar{V}_s vs. Bumper Parameter, Z_1

(Ref 2:195)

Using the penetration formula for a velocity 10,000 ft/sec, equation (4), the thickness of the inner facing required to stop the slower fragments is calculated.

$$\begin{aligned}
 t_2' &= 1.5(0.172)V_s^{0.893}\rho_a^{0.979}S_2^{-0.457}\rho_2^{-0.35}\bar{V}_s^{0.33} \quad (4) \\
 &= 1.5(0.172)(10,000)^{0.893}(0.0821)^{0.979}(940)^{-0.457} \times \\
 &\quad (0.0476)^{-0.35} (497 \times 10^{-9})^{0.33} \\
 &= 0.230 \text{ in}
 \end{aligned}$$

Therefore, at least 0.230 inches of polyester terephthalate is needed to stop the slower meteoroid fragments.

Weight

The weight per unit area of the wall necessary for meteoroid protection is

$$\begin{aligned}
 \text{For face 1: } & 144(0.0916)(0.183) = 2.410 \text{ lb/ft}^2 \\
 \text{For core: } & 144(0.00116)(0.409) = 0.057 \text{ lb/ft}^2 \\
 \text{For face 2: } & 144(0.0476)(0.230) = 1.579 \text{ lb/ft}^2 \\
 \text{Total: } & 4.046 \text{ lb/ft}^2
 \end{aligned}$$

Discussion

Based on a probability of no penetrations of 99.9%, a composite wall using 181 style glass cloth, polyurethane foam, and polyester terephthalate is designed. At least 0.183 inches of 181 style glass cloth is needed to fragment the incoming meteoroid, at least 0.409 inches of polyurethane foam is needed to absorb the fast meteoroid particles, and at least 0.230 inches of polyester terephthalate is

needed to stop the slow meteoroid particles. This gives a total thickness of 0.822 inches and assures that a probability of no meteoroid penetration of 99.9% exists.

Appendix C

Sample Calculations for Determining
the Proton Range in Polyester Terephthalate

This appendix gives the sample calculations for determining the proton range in polyester terephthalate presented in Table VI. The equations used in this appendix are presented, discussed, defined, and referenced in Chapter V. The proton energy used in this sample calculation is 30 Mev. The material, polyester terephthalate, contains 8 atoms of hydrogen, 10 atoms of carbon, and 4 atoms of oxygen. By using the atomic weights and atomic numbers of these elements, the average atomic weight (\bar{A}) and the average atomic number (\bar{Z}) of polyester terephthalate are found to be 8.735 and 4.545 respectively. This gives an $\bar{A}/2\bar{Z}$ ratio of 0.9609.

For materials with a low atomic number, the ratio of the ionization potential (I) to the atomic number (\bar{Z}) is assumed to be 13.5 ev. This ratio gives an ionization potential for polyester terephthalate of

$$I = 13.5 \bar{Z} = 13.5(4.545) = 61.3575 \text{ ev}$$

The function x is defined by equation (11)

$$x = \text{Log} (I/I_{A1}) \quad (11)$$

therefore

$$\begin{aligned}x &= \text{Log } (61.3575/166) \\&= -0.4330\end{aligned}$$

and

$$\begin{aligned}x^2 &= 0.1875 \\x^3 &= -0.0812\end{aligned}$$

With a proton energy of 30 Mev, the values of G_i are found from Table 1 of Ref 18:1047.

$$\begin{aligned}G_1 &= 0.430 \\G_2 &= 0.180 \\G_3 &= 0.136\end{aligned}$$

The value of G is determined from equation (1))

$$G = 1 + G_1x + G_2x^2 + G_3x^3 \quad (10)$$

Substituting into this equation, the value of G is determined.

$$\begin{aligned}G &= 1 + 0.430(-0.4330) + 0.180(0.1875) + 0.136(-0.0812) \\&= 0.8368\end{aligned}$$

Again from Table 1 of Ref 18:1047 with a proton energy of 30 Mev, the value of $\phi_{A1}(T_p)$ is found to be

$$\phi_{A1}(T_p) = 1.1253$$

Substituting the above values into equation (9)

$$RE(T_p, I) = RE(2\text{Mev}, I) + (\bar{A}/2\bar{Z}) \phi_{A1}(T_p) G \quad (9)$$

and neglecting the first term on the right hand side of the equation, the range is found to be

$$\begin{aligned} RE(T_p, I) &= 0.9609(1.1253)(0.8368) \\ &= 0.905 \text{ gm/cm}^2 \end{aligned}$$

Therefore, the proton range of a 30 Mev proton in polyester terephthalate is 0.905 gm/cm^2 .

Appendix D

Personal Correspondence

This appendix contains three letters sent to the author as a result of his inquiries. On 3 October 1965, letters were sent to four corporations requesting information on the environmental effects on and the engineering properties of the materials proposed in this study. A letter dated 22 October 1965 from Mr. Nels S. Hanssen of the GCA Viron Division is shown on pages 107 through 111. A letter dated 28 October 1965 from Mr. N.O. Brink of the Whittaker Corporation is shown on page 112. On 16 November 1965, a letter was sent to Mr. N.O. Brink requesting the shear yield stress of polyester terephthalat and the permeability to oxygen and nitrogen of 181 style glass cloth (urethane resin moisture cured). A letter dated 22 November 1965 from Mr. N.O. Brink is shown on pages 113 and 114.

GCA VIRON DIVISION

A Division of GCA Corporation

7585 Viron Road N.E., Minneapolis, Minnesota 55432 Telephone: 612-786-4700

October 22, 1965

Captain M. R. Keating
Bldg. 640 Box 4252
Wright Patterson AFB, Ohio

Dear Captain Keating:

I am enclosing tables which we have compiled, listing some material properties which may be useful to you.

In regard to the effects of radiation, whether electromagnetic or high energy particles (protons and electrons), the following information is offered.

Mylar

1. Fails at an absorbed dose of $.83 \times 10^8$ rads from gamma rays.
2. 50% decrease in elongation at 2×10^8 rads of electron radiation (Van de Graff).
3. Threshold damage to Mylar occurs at an absorbed dose of 4.4×10^6 rads of radiation.

In general, Mylar crosslinks and becomes more brittle. At first, the tensile strength increases which may actually be desirable. Mylar is considered as a good performing material when exposed to space radiation. This fact is evidenced by the performance of the Echo satellites.

Polyurethane Foam

There is no specific information available on radiation effects on polyurethane foam, however, an isocyanate based elastomeric material has the best radiation resistance of 10 common elastomers. Moderate damage begins at an absorbed dose of 7.5×10^7 rads. Since the urethane linkage is present in both the foam and the elastomer, the inference can be made that the foam will behave in a similar manner.

Captain Keating

-2-

October 22, 1965

181 Style Glass Cloth

Since the radiation resistance of organic polymeric materials such as epoxies, polyesters, and phenolics, is greatly enhanced by fiberglass reinforcement, it may be expected that 181 cloth, an inorganic material, will perform satisfactorily in a radiation environment.

181 Cloth (urethane resin moisture cured)

The information in the preceding two paragraphs apply to this material combination.

Polyvinylidene Chloride

This material decreases in tensile strength under gamma radiation which indicates chain scission. Investigators have found that Saran darkened rapidly and lost all tensile strength at about 5×10^8 rads. Hydrogen chloride gas is evolved upon this polymers degradation. The damage threshold for vinylidene chloride materials is estimated as 4.1×10^6 rads.

The vacuum of space alone is not expected to harm the engineering properties of the materials since they are all of very high molecular weight and have very low vapor pressures. However, the cumulative effects of radiation, vacuum, and high temperatures may accelerate the degradation processes.

For information and data in greater detail, I recommend the following publications:

1. Expandable Structures Design Handbook. ASD-TDR-63-4275. W.P.A.F.B., Ohio 1965
2. Frank A. Bovey, The Effects of Ionizing Radiation On Natural and Synthetic High Polymers. Inter-Science Publishers, New York, 1958
3. Materials In Design Engineering, Materials Selectron Issue, October, 1962
4. L. D. Jaffe, L. B. Rittenhouse, Behavior of Materials in Space Environments, ARS Journal, March 1962
5. Space Materials Handbook, Second Edition, ML-TDR-64-40, W.P.A.F.B., Ohio January 1965

I hope this information will be of use to you.

Very sincerely yours,


Nels S. Hanssen

TABLE 1
PLASTIC FILM

<u>Film</u>	<u>Mylar</u>	<u>Saran</u>
1. Specific Gravity	1.39	1.68
2. Tensile Strength psi	23,000	7 to 15,000
3. Yield Point psi	12,000 (490%)	
4. Modulus of Elasticity psi	550,000	70 to 200,000
5. Temperature Range		
High	300° F	290° F
Low	-75° F	
6. Heat Transfer Coefficient BTU/hr/ft ² /°F/	1.035/in	.503/ft.
Coefficient of Expansion in/in/°F	1.5 x 10 ⁵	8.78 x 10 ⁵
Specific Heat	.315 cal/g-°C	.32 BTU/lb/°F
Radiation, Beginning of:		
Moderate Damage	4.4 x 10 ⁶ rads	4.1 x 10 ⁶
Serious Damage	8.7 x 10 ⁷ rads	4.5 x 10 ⁷

TABLE 2
TYPICAL VALUES OF
POLYURETHANE FOAM
Open Cell

Density	lbs/ft³	2
Tensile Strength		16 to 35 psi
Compression Set 50%		6
Deflection	lbs/in²	
25%		0.50
65%		0.85
Temperature		
High (about)		250
Low (about)		-50

TABLE 3

181 Style GLASS CLOTH PROPERTIES

1. Construction	
Warp	57
Fill	54
2. Yarn	
Warp	225-1/3
Fill	225-1/3
3. Thickness	0.009 in
4. Weight	8.9 oz/yd ²
5. Tensile Strength (Breaking)	
Warp	350 lbs/in
Fill	340 lbs/in
6. Specific Gravity	2.54



NARMCO RESEARCH & DEVELOPMENT DIVISION
3540 Aero Court · San Diego, California 92123 · (714) 277-3040

28 October 1965

Captain Michael R. Keating
Air Force Institute of Technology
Bldg. 640, Box 4252
Wright-Patterson Air Force Base
Dayton, Ohio

Dear Capt. Keating:

Please excuse the delay in answering your request for information regarding materials for expandable structures. I was planning on sending you a copy of NASA Contractor Report CR-121 but we no longer have any extra copies in our library. This volume summarizes the work Narmco R&D performed in connection with elastic recovery materials for expandable space structures.

Enclosed is a copy of Section III from CR-121 which described the investigation of elastic recovery materials. Some of the information you requested on materials is included in this section. Perhaps the library at the Air Force Institute of Technology would have a copy of NASA Contractor Report CR-121, dated December 1964, entitled "Development and Evaluation of the Elastic Recovery Concept for Expandable Space Structures" by N. O. Brink, B. C. Anderson, C. E. Thompson, and C. E. Wolcott.

Good luck on the writing of your thesis.

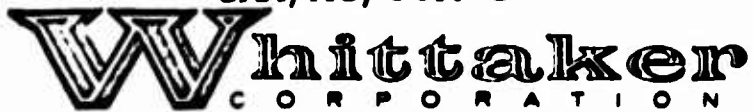
Very truly yours,

WHITTAKER CORPORATION
Narmco Research & Development Division

N. O. Brink
Sr. Research Engineer

NOB/lw

Enclosure



NARMCO RESEARCH & DEVELOPMENT DIVISION

3540 Aero Court • San Diego, California 92123 • (714) 277-3040

22 November 1965

Captain Michael R. Keating
 Air Force Institute of Technology
 Bld 640, Box 4252
 Wright-Patterson Air Force Base
 Dayton, Ohio 45433

Dear Captain Keating:

The following information may be useful in your project.

1. The literature does not cite shear yield stress for polyester terephthalate (Mylar) films. However, since this particular film is biaxial in strength characteristics, perhaps the shear strength can be approximated by the use of strength ratios from MIL-HDBK-17, Plastics for Flight Vehicles. The use of the ratios of yield to ultimate strength applied to the tensile strength of 181 style reinforcement would provide a reduction factor. For example, using the tensile strength of Mylar as 25,000 psi, a comparable reduction ratio of 181 style glass cloth reinforced polyester would be:

$$F_{sy} = F_{tu} \left(\frac{F_{ty}}{F_{tu}} \right) \left(\frac{F_{su}}{F_{ty}} \right) \left(\frac{F_{sy}}{F_{su}} \right) = \frac{F_{sy}}{F_{tu}} = \frac{1,420}{38,000} = .0375 F_{tu}$$

where values for F_{sy} (proportional limit) and F_{tu} were taken from MIL-HDBK-17. Applying this ratio to the Mylar film, tensile strength would give:

$$F_{sy} = 25000 (.0375) = 940 \text{ psi}$$

Note that the high elongation of the Mylar probably would cause this number to change.


2. The shear yield stress of 7700 psi cited on Page 198 of CR-121 is an estimated value for typical laminate. Note that this yield stress is not the same as the proportional limit in Item 1. We assumed that a relatively high elongation could occur to obtain this stress level.

-
3. I checked some Air Force reports on moisture cured urethane resin laminates to determine the permeability of the materials. The companies working with this material apparently recognize that it is porous and use impervious liners, such as Saran, to prevent gas loss. Hence, no permeability data were found for these materials.

I hope this information, while not a direct answer to your inquiry, will assist you in your work.

Sincerely yours,

WHITTAKER CORPORATION
Narmco Research & Development Division



Norman O. Brink
Sr. Project Engineer

OB:js

Vita

Michael Roy Keating was born [REDACTED]
[REDACTED] the son of [REDACTED] and
[REDACTED] In 1953, he was graduated from
[REDACTED] He was appointed to
the United States Military Academy in June 1953, and was
graduated with the degree of Bachelor of Science in June
1957. After receiving his commission as Second Lieutenant
in the USAF, he entered active duty in June 1957. He
reported for flying training immediately after graduation
and received his wings in September 1958. Before coming
to the Air Force Institute of Technology, he was assigned
as a Crew Commander with the 350th Bombardment Squadron,
100th Bombardment (Medium) Wing (SAC) at Pease AFB, New
Hampshire.

Permanent address:

[REDACTED]

This thesis was typed by Mrs. Judy Ann Click and Mrs.
Loretta J. Schwing.